SPAWAR
Systems Center
San Diego

Non-Lethal Swimmer Neutralization Study

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ADMINISTRATIVE INFORMATION

EXECUTIVE SUMMARY

Applied Research Laboratories, The University of Texas at Austin (ARL: UT) was tasked to study the means and equipment for non-lethal methods to deter swimmers and scuba divers from restricted areas. This work included identification and evaluation of existing technologies, as well as review of research in security, acoustics, biology and other fields. ARL: UT has studied swimmer detection for more than 30 years, and has developed many systems for Navy use including a CW Doppler sonar used during the Vietnam War. [1-3] In the 1990s, ARL: UT developed several sonars for swimmer detection, including the AN/WQX-2, [4,5] which was integrated into the Waterside Security System (WSS) and installed at several Navy sites worldwide.

As the capability to detect swimmer threats has improved, questions about how to respond to potential threats have arisen more frequently. Historically, grenades and small arms, as well as low frequency active sonars, have been utilized against subsurface threats. Explosives are effective, but lethal against threats; small arms are available to security personnel, but are also lethal weapons and difficult to target against a subsurface threat. Shipboard low frequency sonars used for mine hunting, anti-submarine warfare, depth sounding, and other tasks have been used because they were available but not necessarily because they were proven as a defensive tool.

The law enforcement "use of force" continuum begins with command presence and escalates through verbal commands to non-lethal force, and finally, to lethal force. While this report focuses on non-lethal force options, it is important to note that deterrence can also be improved by expansion of existing command presence capabilities: patrol boats, floating barriers, and other visible waterside indicators that announce to potential attackers that the site is a hard target. Similarly, improved capability for delivery of verbal commands to an approaching potential threat (such as surface public address systems and subsurface acoustic diver recall systems) could deter some intruders. Failure of an intruder to respond appropriately to these warnings could imply hostile intent. Security personnel must be able to determine intent of an intruder in order to make an appropriate use of force decision. In the absence of clear hostile intent, use of lethal force is difficult to justify.

Various technologies have been developed as non-lethal weapons for law enforcement, but most of them are not suitable for deterring swimmers and scuba divers, because they are not designed for subsurface use. These existing technologies, as well as equipment currently used for diver deterrence and communication, were evaluated in this study. Underwater surface-to-seafloor barriers are potentially effective but have extremely high cost. The use of trained marine mammals, such as exists with the U.S. Navy's MK6 marine mammal system, has been shown to be highly effective over many years. However, only one of these systems is available, located in San Diego and operated by Mobile Unit Three. The MK6 Marine Mammal System has been a fielded fleet system since the 1970's. The most practical near-term solution for swimmer deterrence is the use of commercially available acoustic and explosive diver recall devices, deployed from a response boat. These solutions are only effective when the location of the threat is known, which assumes that detection capability already exists. Sonar remains the only method by which both surface and subsurface threats can be detected; surface targets (depending on size) can also be detected using radars, cameras, thermal imagers or human observers.

The most promising long-term solution for a non-lethal diver threat response is the development of a low frequency sound source designed specifically to produce signals likely to cause discomfort in human divers. Spark gap sound sources are an existing technology that have been used for other

underwater sound applications, but never seriously evaluated as a swimmer deterrent. A spark gap sound source can produce high intensity, low frequency impulsive sound in a portable system suitable for pier-side or shipboard use. A review of existing literature on the effects of high intensity, low frequency sound on divers indicates that this type of sound may cause Bioeffects useful for non-lethal swimmer deterrence. This device could be used as a stand-alone system, deployed pier-side or from a response boat, or used in conjunction with swimmer detection sonar.

Future efforts in this area should focus on increased visible, floating barrier and patrol boat presence along waterside areas, use of diver recall devices by waterside security forces, and animal and human testing of the deterrent Bioeffects of the spark gap sound source.

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1. THE NEED FOR A NON-LETHAL RESPONSE

Interest in non-lethal weapons continues to grow [6-10] as weapons such as pepper spray and blunt impact munitions become commonplace in law enforcement. [11] Non-lethal weapons are particularly appropriate for use in situations where a person (or persons) is attempting to enter a secured area to carry out a political protest rather than a violent attack. [12] In this situation, the violator is typically unarmed and poses no clear lethal threat, making justification of defensive lethal force more difficult to obtain from the courts of law and public opinion. A non-lethal weapon that causes enough temporary discomfort to stop the intruder could be used as an intermediate step between verbal commands and use of lethal force. [13]

The use of force decision becomes more complex when the subject is a swimmer or a diver approaching a military installation. Even for those limited sites that have specialized detection capability, the intent of the subject is difficult to assess. Rules of engagement are only useful if it is possible to determine hostile intent. [14] For subsurface threats, visual assessment and verbal communication are possible with specialized equipment, such as camera-quality sonar and an acoustic diver recall system deployed from a response boat. At present, this capability is not readily available to force protection personnel, who currently have only two options: wait for an attack to begin, or pre-emptively use lethal force. Waiting is the "safe" response, as intrusions into military facilities are rare, and intrusions by those intent on violence even more rare. The risk is that allowing the attacker a first strike before making any response can have tragic consequences.

The October 2000 attack on the USS Cole (DDG-67) was not caused by a swimmer or a diver, but it easily could have been. A typical diver can swim 100 yards in three minutes, at a one-knot pace. Assisted by a one knot current in the right direction, that pace can double to 200 yards in three minutes. Large standoff zones and long sonar detection ranges are essential for providing security forces sufficient time to locate and respond to an intrusion, but in many situations, these luxuries are not available. Clearly, a need exists for force protection personnel to have immediately accessible non-lethal responses that can be used without the administrative, legal, moral and political burdens associated with use of lethal force. [15-19] While this report focuses on non-lethal force options, it is important to note that deterrence can also be improved by expansion of existing "command presence" capabilities: patrol boats, floating barriers, and other visible waterside indicators to potential attackers that the site is a 'hard' target.

2. DETECTION

The term "swimmer" is used, in this report and elsewhere, to refer to both surface swimmers and scuba divers. While these two threats are frequently grouped together, each poses unique detection and deterrence problems. Radars, thermal imagers, cameras, sonar and simple visual observation can all be used to detect a surface swimmer. Many levels of response to a surface threat are possible, from simple physical force to nets, small arms and grenades. The subsurface threat presents a more difficult problem, because reliable detection is only possible by use of high-resolution active sonar or Navy trained dolphins or sea lions. When seas are calm, and the diver uses open circuit scuba gear at a shallow depth, visual observation and thermal imaging may also be used for detection. At night, in rough, deep, warm, and/or turbid water, a diver is effectively invisible to all sensors except mechanical or biological (e.g. dolphin) sonar or the eyes and ears of the sea lions.

A common misconception regarding swimmer detection is that passive sonar is capable of detecting all types of swimmers and divers. Passive sonar is commonly used to listen for sounds produced by propellers, motors, marine mammals, and anything else that makes significant noise underwater. The use of passive sonar has been investigated at ARL: UT several times in the past. [1,4,5,20,21] In general, swimmers and divers do not produce self-noise above the ambient noise levels in water. [22] Open circuit scuba and swimmer propulsion equipment produce periodic noise that can be detected and automatically classified, [21] but unassisted swimmers, such as the intruder who entered the British submarine base at Faslane, Scotland, in April 2001, [23] and divers using closed circuit (rebreather) equipment, are extremely difficult to detect using passive sonar. Another limitation of passive sonar is that it can determine only bearing and cannot provide the user with "range to target" information. Range and bearing are both required if a response force is to intercept the threat.

High power, low frequency sonar commonly used for anti-submarine warfare, depth sounding and large-object detection are also poorly suited for swimmer detection. Many of the high power, low frequency sonar aboard U.S. Navy surface ships are defined as hazardous to divers in the Navy Diving Manual [24] and should be considered weapons rather than detection sensors.

As of this writing the AN/WQX-2 is the Navy's swimmer detection sonar. [25] The AN/WQX-2's sonar parameters (beam width, frequency, transmit power, etc.) were optimized for swimmer detection. This sonar can automatically detect, track, classify and alert on swimmer and diver targets within its 360-degree, 800-yard coverage area. An AN/WQX-2 soundhead is shown in Figure 2.1.

Figure 2.1. AN/WQX-2 Soundhead [26]

The AN/WQX-2 provides the user with the range and bearing of the detected target relative to the sonar. When interfaced to the C3D console developed by Space and Naval Warfare Systems Center, San Diego (SSC San Diego) for the Waterside Security System, this information is converted to a GPS position. A sample of the AN/WQX-2's display is shown in Figure 2.2, with a swimmer track (#482) displayed in red. The sonar tracks all moving objects in its coverage area, including fish schools, marine mammals, drifting debris and bubbles from boat wakes. It uses a complex set of track analysis heuristics and image classification algorithms to separate these nuisance tracks from tracks produced by swimmers and divers.

Figure 2.2. AN/WQX-2 Swimmer Track [26]

Other swimmer detection sonars are currently in development or production by commercial companies as well as foreign governments. These sonars vary widely in cost, size, availability, and performance. As part of the Navy's Waterside Security System (WSS) project, SSC San Diego continues to survey the swimmer detection sonar market to remain aware of the capabilities and status of currently advertised models. Lower operating frequencies provide longer detection ranges but require larger soundheads. Higher frequencies limit maximum detection range but result in smaller, more portable soundheads. As part of the ongoing market survey, SSC San Diego and ARL: UT will evaluate several commercial high-resolution portable sonars to determine whether their swimmer detection capabilities can be improved by real time interpretation of their data by automatic processing software developed for the AN/WQX-2. The smaller soundheads will not have coverage areas or alert ranges as large as that of the AN/WQX-2, but they may offer acceptable performance for those users willing to trade reduced response time and coverage area for portability.

Subsurface threats occur in a three-dimensional space (latitude, longitude, and depth), but no depth information is needed for a surface swimmer threat. Currently, no swimmer detection sonar (including the AN/WQX-2) provides depth information to the operator, and depth cannot be determined through visual observation. It is possible that an inexpensive fish finding sonar could be used aboard a patrol boat to determine depth of an identified diver, but this concept has not been demonstrated as of this writing. Without an accurate three-dimensional location for the target, it is difficult to effectively use short-range, non-lethal weapons that are often used against land-based targets. The specific limitations to application of existing, non-lethal weapons to swimmer deterrence will be discussed in a later section.

One other technology worthy of consideration is passive millimeter wave detection. [27] These detectors are similar to infrared imagers, except that they receive signals in the 27-100 GHz band and are unaffected by ambient temperature. These sensors are only useful for detection, not as a weapon, but they may provide an enhanced capability to detect surface swimmers at night. Because surface swimmers travel along the air-water boundary, their target strength for sonar, radar, visual and infrared sensors is degraded particularly in high sea states. It may be possible to build a simple "beam break" detector based on a passive millimeter wave sensor with a broad beam and a threshold circuit that alarms when a body that radiates millimeter waves, such as a human, passes within the

beam. However, until testing is performed to measure detection range of surface swimmers using passive millimeter sensor, the feasibility of this idea cannot be assessed.

3. SEARCH PARAMETERS

The search for a suitable non-lethal swimmer deterrent device was bounded by several parameters. The device should cause discomfort, pain or temporary injury. Permanent effects such as deafness, blindness, maiming and crippling were considered unacceptable. Ideally, the device would have an adjustable power level, take effect quickly, and require minimal training for the operator to safely use. The device would also be practical with regard to size, cost, and the probability that it could be integrated into existing equipment, capabilities and tactics for force protection. The ideal device should be practical for both harbor and shipboard use, and be useful even if swimmer detection sonar is not available to provide the swimmer's location.

The most difficult search parameter was that the devices rely on a well-documented Bioeffect that would produce consistent results in nearly all individuals. Pepper spray (*Oleoresin capsicum*) is widely considered an effective non-lethal weapon, [28-30] yet many law enforcement training programs now require officers to be sprayed with pepper spray and perform follow up tasks such as punching a heavy bag for several minutes. [31,32] This training is intended to enhance the officers' understanding of the effects of pepper spray and demonstrate that a determined attacker may be capable of continuing to fight after being sprayed. In addition, a small number of fatalities have occurred from law enforcement use of "safe" technologies such as pepper spray [30,33-37] and "bean bag" impact munitions. [31]

In contrast, handgun rounds are universally accepted as lethal force, but the actual survival rate for handgun shootings is surprisingly high. Less than one-third of people shot with handguns die from their wounds [38-40]. These facts are mentioned only to remind the reader that all weapons, including non-lethal ones, have practical limitations and are not 100% effective against all targets in all situations. The mindset, determination, and pain tolerance of the attacker can limit the effectiveness of any weapon, lethal or non-lethal. [41] The terms *non-lethal*, *less-than-lethal*, and *less-lethal* have all been used to describe weapons designed to cause temporary injuries. The authors prefer the term *less lethal* to *non-lethal*, because it reminds the user that fatalities can occur from the weapon's use. *Less-than-lethal* may be more grammatically correct, but is cumbersome. The term "non-lethal" is most commonly used within the military community, and that term will be used throughout the remainder of this report.

Identifying a "safe" non-lethal weapon is difficult, because the underwater environment is an inherently hazardous one. Any time a diver's physical or mental state is impaired, there is a risk that the diver could suffer serious injury as a result. [42] It is important to note that there is a reasonable probability that any non-lethal weapon used against a scuba diver could cause death as a secondary consequence of the weapon's effects. [43,44] Potential users of non-lethal weapons against swimmers should be prepared to render medical aid for a variety of dive emergencies including drowning and decompression sickness caused by rapid ascension. Ideally, basic training in diver first aid should be incorporated into any training related to use of non-lethal swimmer deterrent devices.

4. EXISTING IN-AIR APPROACHES

A variety of technologies are used for other non-lethal responses, including "soft" projectiles, chemical agents, restraints, physical force, electrical devices, and sound- and light-producing devices. The next sections discuss the applicability of these known approaches to swimmer deterrence.

4.1 PROJECTILES

Non-lethal projectiles take a variety of forms, from "bean bag" rounds to rubber bullets to "pepper balls" made from a chemical agent. The projectiles are designed to be fired from a variety of existing platforms, including shotguns, grenade launchers, and tear gas guns. [8,11,45-47] In all cases, this technology is not suitable for swimmer deterrence. Delivery of these munitions requires precise targeting and accurate shooting, neither of which is feasible against a moving, subsurface target at unknown depth and changing range. Additionally, no known data exists about the specific ballistics of non-lethal projectiles fired from air into water, and what effect the denser, frequently turbulent medium would have on velocity, accuracy, and general performance of those projectiles against a waterborne target. The most likely effects would be a dramatic reduction in velocity, and that waves and current would cause the projectiles to veer off course.

Figure 4.1. Non-Lethal Munitions [48]

4.2 CHEMICAL AGENTS AND ELECTRICAL DEVICES

Chemical agents are widely used as non-lethal weapons because in air, they can cover a wide area, have temporary effects, and are easily deployed. Pepper spray used against a surface swimmer, would result in risk of death by drowning (as a result of breathing problems induced by the pepper spray) if the swimmer was not quickly rescued from the water. Another significant outcome is the possibility that the chemical agent would have little effect on the swimmer, since flushing the subject with large quantities of fresh water is the primary decontamination process for exposure to pepper spray. [30,35-37] Against subsurface targets, chemical agents, particularly those in gaseous form, will have no effect because the divers have their own breathing apparatus. Chemical agents, in gas or liquid form, do not dissipate in water easily and cannot be easily delivered to a target at unknown depth. Electrical devices currently used as non-lethal weapons are close range or contact devices such as stun guns and tasers. [49-52] These devices are not practical as swimmer deterrents because of the

difficulty in targeting these weapons to the threat. Even the most likely application, the firing of a taser from a patrol boat at a surface swimmer, has minimal chance of success.

Figure 4.2. M18 Taser Weapon [53]

The taser works by firing wires (with barbed ends) into the subject, providing an electrical connection between the taser and the subject. Eighteen watts, 133 milliamperes and 50,000 volts of electricity applied to the subject cause electro-muscular disruption. The M18 Taser, shown in Figure 4.2 and Figure 4.3, has a maximum range of fifteen-feet. [53] This range limitation would require the patrol boat driver to keep the boat no more than fifteen-feet from the surface swimmer before, during and after the taser is fired. If the fifteen-foot limit is exceeded, the electrodes lose contact with the subject and could fall into the water, short-circuiting the taser. The taser also puts the subject at immediate risk of drowning. Personnel would have to be prepared to take lifesaving action after the taser was fired. At best, the taser is only a reasonable solution in a very special combination of circumstances, and is not a general-purpose solution.

Figure 4.3. Taser Demonstration [53]

4.3 PHYSICAL FORCE

The simplest form of non-lethal force is physical restraint such as unarmed techniques applied by force protection personnel against individuals. This approach could be used for swimmer deterrence if the general location of a subsurface threat was known. For unarmed defense to be successful, multiple divers would be necessary to search a volume of water. Determining the location of a subsurface threat requires a three-dimensional search in a typically low-visibility environment. A diver threat swimming in at a depth of 40 feet could easily be missed by a diver searching at a depth of 10 feet. A handheld sonar, such as the AN/PQS-2 (A), ARL: UT Integrated Navigation Sensor System [20] (INSS) or APL:UW high-resolution acoustic lens [54] could be used to assist divers in

target location. Each of these sonars is currently in use by Navy diving activities for mine hunting and other small object location tasks.

If the response divers were to make contact with the intruder(s), the response divers could attach an inflatable flotation device or a similar device to the intruding divers. It is also very likely that the responding divers have to engage in underwater hand-to-hand combat that could quickly turn from application of restraints, to lethal combat, due to the risk of drowning and high probability that one or both divers would have a dive knife easily available as a weapon. The cost and logistics associated with having a dive team on continuous standby for immediate deployment, combined with the low probability that the divers would make contact with the intruder makes this option impractical.

Figure 4.4. Diver Using INSS Handheld Sonar [20]

The U.S. Navy's MK6 Marine Mammal System uses the natural sonar of dolphins to locate objects from mines to swimmers and divers in the water column. This system can detect and mark the location of an intruder. This system was deployed to Vietnam in 1970-71, the Persian Gulf in 1987-1988 and was also tasked to provide security in San Diego harbor during the 1996 Republican National Convention. The Space and Naval Warfare Systems Center, San Diego (SSC San Diego), provides support for this system with replenishment dolphins, hardware, training, personnel and documentation (ref. 55). However, there exists only one fielded MK6 Marine Mammal System so availability to several locations simultaneously is limited.

Figure 4.5. Marine Mammal [56]

   Underwater remotely operated vehicles (ROVs) are yet another alternative means of force. An ROV can be equipped with a camera or imaging sonar to provide additional detection, classification, and localization information about the intruder, and the ROV could also be used to harass and pursue the diver within the limits of the ROV's tether. The primary limitation of an underwater ROV is the need for a tether, which mandates that it either operate close to a pier, or launch from a craft large enough to support the ROV and its umbilical cable. Significant improvements have been made in the development of underwater "modems" that could enable development of wireless controls for underwater ROVs. Typical commercial telesonar modems have a maximum data rate of 2400 baud [57] in ideal conditions, which is insufficient to provide the operator with real-time video updates. Because of the limitations of sound transmission underwater, data rate decreases and error rate increases as the distance between the transmitter and receiver increases. At present, the technology for a practical, wireless underwater ROV does not exist in the commercial environment.
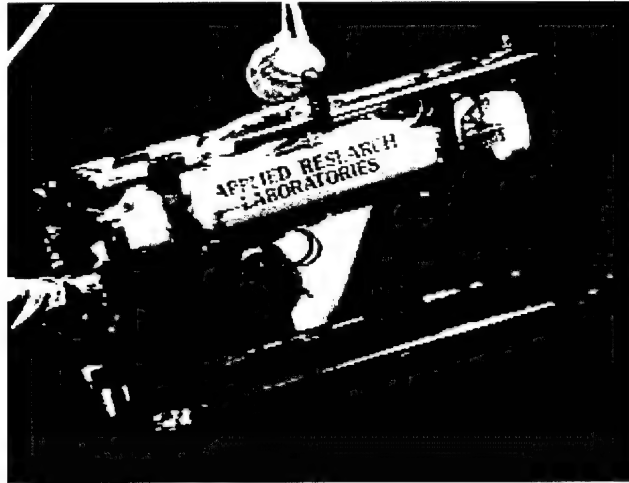
Figure 4.6. Underwater Remotely Operated Vehicle [58]

An underwater ROV could have value both as a swimmer localization and identification tool and a possible deterrent, but the deterrent value is negated if the ROV can be easily outmaneuvered, outpaced, or damaged by a human diver equipped with nothing more than a diving knife. Small autonomous ROVs, such as those in development for DARPA on the Microhunter program, [59] might be deployable from a response boat or a pier. The Microhunter ROVs are intended to work in groups to search an area or locate objects.[60] An internal research program at ARL: UT has also developed a low-cost autonomous underwater vehicle capable of navigating a pre-programmed course.[61] The problems of how these small ROVs would determine the depth of the diver threat, and what payload the ROVs could carry to deter the diver(s) would have to be solved in order to make this technology a viable solution.

Figure 4.7. Small Autonomous Underwater Vehicle [61]

A surface ROV, such as the OWL (also known as the Unmanned Harbor Security Vehicle), [62] could operate without a tether. However, without the capability to operate at the same depth as the attacking diver, a surface ROV's ability to deter an approaching subsurface threat is virtually nil. All types of ROVs have high annual costs and require maintenance and operator training. Another weakness in this approach is the inability to deal with a multiple diver, multiple approach problem. A single ROV would only be able to deal with a single threat (single diver or dive pair) at a time. The U.S. Navy's MK6 Marine Mammal System, operating with superior mobility, speed, and natural sonar is capable of deterring multiple threats in a short time. Again, however, since only one of these systems exist, availability of this system may be limited, and dependent upon military priorities. The mammal must deal with each threat one at a time, which limits the number of threats that can be

deterred in a short period. The diver recall and acoustic based approaches described in later sections can affect a large volume of water, which would deter all divers within that area simultaneously.
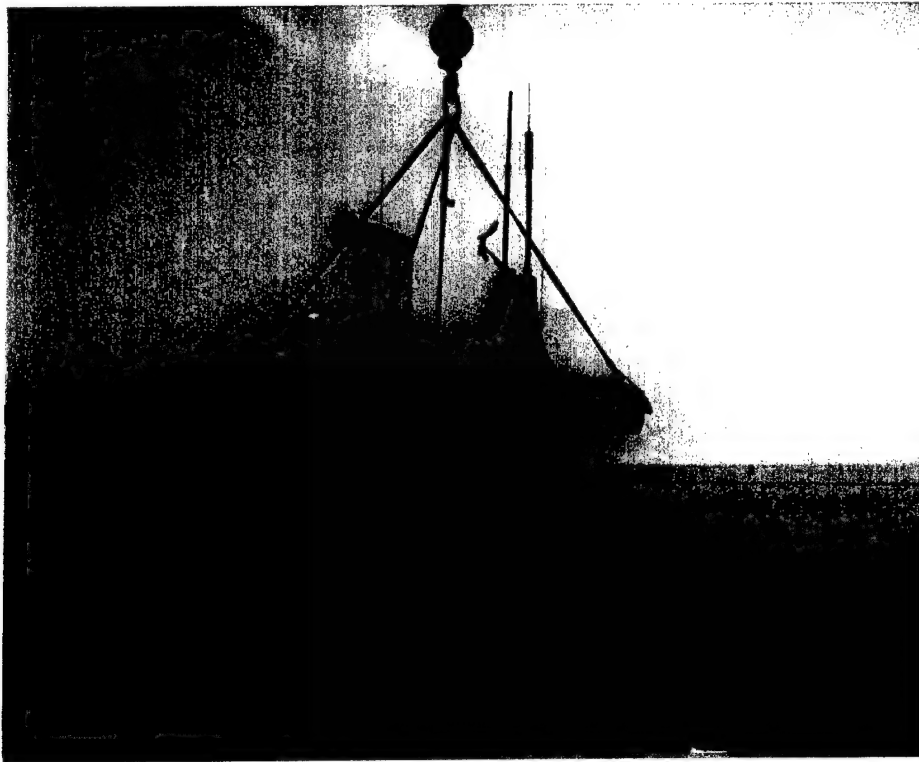
Figure 4.8. OWL Surface ROV [62]

4.4 RESTRAINTS

The use of barriers and nets to block underwater access to secured areas is another alternative to deter swimmers and divers from entering a protected area. [63] Fixed barriers are a stand-alone system in that no precise detection/localization system is required. The barrier prevents access and produces an alarm when cut, which provides the response force with the diver's location. A Swedish company, Safe Barrier Systems (SBS), a division of NCC Stockholm, has developed a barrier system for swimmer deterrence. The company has fielded systems in Saudi Arabia, in Sweden, and in Florida at the Florida Power and Light Co. nuclear generator just north of Palm Beach at Port St. Lucie, Florida. The British Navy recently evaluated this system [64]. The Safe Barrier net system consists of 8mm diameter galvanized high tensile steel cable, coated in polyethylene for electrical integrity and polyurethane jacket for physical resistance against abrasion. The continuous cable is jointed using molded steel reinforced with polyurethane to form a mesh grid. The grid size best suited for swimmer deterrence is 250 x 250mm. Testing performed by U.K. researchers indicated that a diver using bolt cutters could form a human-sized hole in 60-90 seconds.

THE NET

The size can be varied to suit customer requirements. Each cross over is sealed with moulded polyurethane material. Sections of the net are joined together with a moulded connection piece which is sealed with Durasil. Neither can be broken without activating the alarm system. The net is ancored at the bottom to a concrete filled tube which sets solid along the contours of the sea bed or secured to fixed structure. The ends are secured to the shore or fixed structure. The entire net and lines securing it are fitted with an alarm system.

The knots in the net are moulded in a polyurethane material and equipped with inside metal reinforcements and cannot be undone without activating the alarm function.

All anchores are equipped with alarm signal line to avoid sabotage

Figure 4.9. Barrier example [63]

The Safe Barrier net can be constructed to provide a number of detection zones, which can be interfaced with a site wide alarm system. Testing indicated that a bypass loop could be used to allow an intruder to make undetected cuts in the net. The zones are typically 50 yards wide by the full depth, which could be as deep as 100-200 feet in some locations. Even in very shallow water (maximum depth of 40 feet or less), there is a large volume of water to search for a diver or an ROV to search, particularly if the visibility is poor. The net is held down to the seafloor by the use of concrete blocks. Depending on bottom type, it might be possible for a diver to slip under the net. The net is supported at the surface by cylindrical buoyancy units of 600mm diameter. These units were considered to be of insufficient height, since a diver with fins could potentially get over them and bypass the net without setting off the alarm. The net system can be equipped with a gate, operated by an air compressor, to allow traffic in and out from the protected area.

Figure 4.10. Barrier with Gate [63]

SBS currently supports 15 sites: including four with gates, but they are not currently manufacturing this net system, due to the infrequent specialized demand for this technology. The costs involved with installing a net are high: the estimate SBS provided was more than $7M for initial installation.

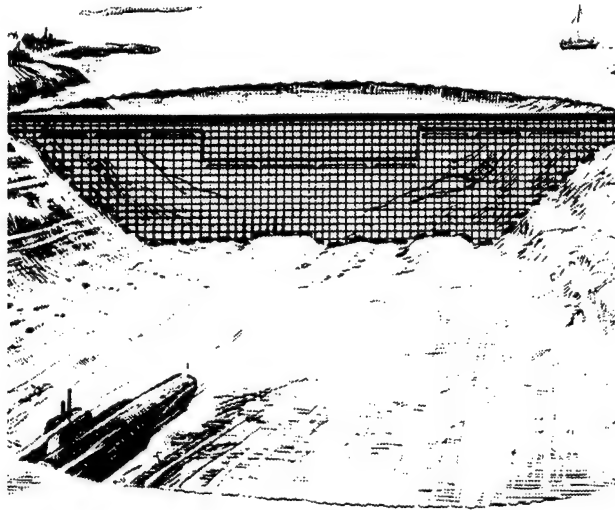Another company also advertises anti-swimmer nets: BEI Security Systems.[65] Their net is called the F-8000, which is a fiber optic alarm net designed to provide physical protection above and under water. Representatives from the Waterside Security System program have received price quotations (cost per square foot), but were unable to obtain information on installation locations with satisfied customers, nor an estimate for a fully installed system. A report from 1989 [66] also mentions a U.K. company that was producing a fiber-optic alarmed underwater barrier under the "Aquamesh" name. An Internet search on that name revealed that Aquamesh is now the brand name of a popular underwater wire mesh used in the aquaculture industry for lobster and crab traps, but no fiber-optic alarmed version of this product could be located.[67] Additionally, one factor not addressed in the U.K. report (or in other documentation related to barriers and nets) was environmental impact. A permanent barrier, particularly one with a grid size small enough to deter a swimmer, will affect the movement of fish schools, marine mammals and other aquatic life. [68] In areas such as Pacific Northwest, this barrier could interfere with salmon migration. Along the southeast Atlantic coast, the barrier could negatively impact manatees and other native marine life.

Surface-to-seafloor barriers, particularly the SBS system, may be reasonable solutions in areas where water depth is shallow and the total area covered is small. In general, their high cost and negative environmental impact make them poor choices for swimmer deterrence. Floating barriers, primarily those designed to stop fast moving surface craft, or barriers that mark restricted areas, would be useful for clearly marking the protected area and preventing surface craft from deploying divers close to pier-side assets.

5. LIGHT- AND SOUND-PRODUCING DEVICES

The devices discussed thus far rely on physical and chemical effects, most of which are reasonably consistent from individual to individual. Non-lethal weapons that rely on restraints and blunt trauma are simple in concept and easy to test. Testing protocols and methods for evaluating chemical agents are well understood, because similar testing is done on food items, drugs, cosmetics, pesticides, and other chemicals in non-weapon applications. The majority of research that has investigated the effects of light and sound on living organisms has mostly focused primarily on vision and hearing. The next section will discuss the use of light- and sound- producing devices for swimmer deterrence.

5.1 LIGHT-PRODUCING DEVICES

Extremely bright lights can be used to cause temporary loss of vision. Several companies, including Laser Products and Stream light, have developed handheld flashlights capable of producing intense light. [69] In the past decade, much has been learned about the use of "light as a weapon" by military and law enforcement personnel. [70] In a low light environment, bright lights can cause an individual's vision to "wash out," causing a form of temporary blindness. Flash-bang grenades, commonly used by military and law enforcement entry teams, produce this same effect [31,32,71].

In 1975, the U.S. Army Materiel Command produced several reports under the "DISPERSE" program, which evaluated the use of sound- and light- producing devices for crowd control. [72-74] One of these reports [72] was a summary report listing references to current research. That reports states,

> "...of the 'mountains' of literature dealing with sound and light, there is virtually a pittance treating the subjects in a manner directly beneficial to the DISPERSE effort. There exists... sufficient technical information to support at least an exploratory investigation of ... aversive audible acoustic stimuli, infrasonic and ultrasonic systems, and bright flashing and flickering light."

Another report [74] contains proposals for experiments to test off the shelf equipment capable of producing audible sound, infrasound (1-20 Hz tones below the normal hearing range), delayed speech and flashing lights. No follow up reports were located during the literature search, and it is assumed that these experiments were not performed or did not produce positive results.

Epileptic seizures can be induced in susceptible people by light and repetitive visual signals, [75,76] but only a fraction of the populace is susceptible to this Bioeffect. [77,78 79] Most data on this topic is anecdotal, or restricted to lab animals. [80-85] One notable exception is the seizures that were reported following broadcast of a particular episode of the "Pokemon" animated cartoon in Japan. [86-88] These seizures, while widely reported, only occurred in a tiny fraction of the total viewing population, confirming previous research. [77] Screen update rate was observed to be a factor in light-induced epilepsy, with 100 Hz refresh rates inducing fewer seizures than 50 Hz rates. [89,90] Another visual Bioeffect is a form of illusory self-motion known as vection, which occurs when a motionless observer is placed in the center of a rotating vertically striped drum. If this mismatch between visual inputs is prolonged (greater than 5 minutes), it is often sufficient to induce motion sickness in susceptible subjects. [91]

Spectra A&M Associates distributed a white paper which described experiments conducted using bright lights flashing at an unspecified frequency, which produced the "Brewster effect". [92] In the mid-90s the Spectra report was made available to individuals working in the swimmer detection field. Although the paper claims that the research was done for the Navy, the literature search performed for our study did not find any other published references to the Brewster effect, or other reports supporting the claims made in this paper. Regardless of the validity of the Brewster effect claims, these techniques are a poor choice for general use in swimmer deterrence because light propagates poorly in seawater.

5.2 SOUND-PRODUCING DEVICES

Unlike light, sound propagates well in seawater, and sonars are used for many applications in the underwater environment, including imaging, swimmer detection, and mine hunting. [93] A single sound-producing device, located near a protected asset, could transfer sound into a large volume of water around the asset as a deterrent. This approach has several benefits: an entire area is protected by a single device, affecting every target within the area, and the Bioeffect increases as the intruders swim toward the protected asset. The weapon's strength is relative to range, and the amount of discomfort experienced is determined by the diver's willingness to approach the weapon.

The critical question related to the use of sound to deter a swimmer is which frequencies, sound levels, and waveforms are required to reliably cause a proven Bioeffect. Since World War II, many experimental devices have been proposed, and some built and tested. [46,50,94-96] In the past five years, interest in non-lethal weapons has grown significantly, and many claims have been made regarding the effects of various frequencies, sound levels, and durations on the human body. [46,97] In particular, charts like the figure below show up in many overviews and books on non-lethal weapons. [98] Typically these charts are published without explanation or supporting data. One goal of this study was to review existing research in order to separate claims based on verified data from those of mere speculation.
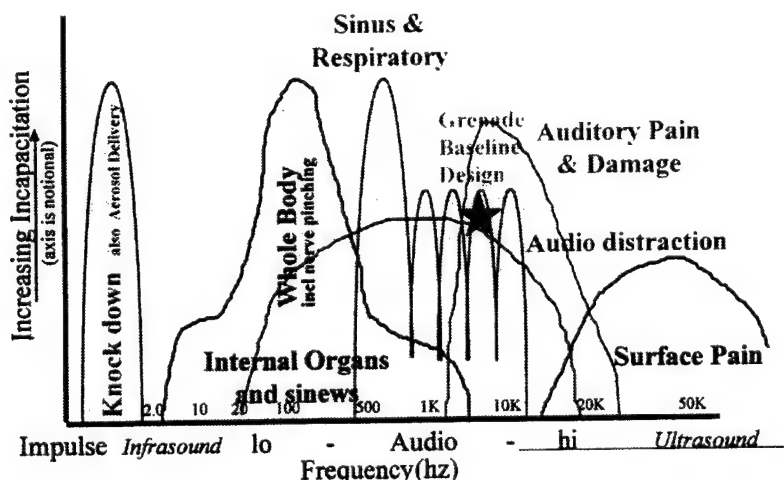

Figure 5.1. Alleged Bioeffects of Sound [99]

5.2.1 Acoustics Terminology

Sound exposure is described by three key parameters: frequency, duration and sound pressure level. Frequency is perceived as pitch, such as a particular note in a musical scale, and expressed in units of Hertz (Hz), which is equivalent to the number of sine wave cycles per second. The frequency range of human hearing is approximately 20 – 20,000 Hz. Frequencies below human hearing are called infrasound (1-20 Hz), and frequencies above human hearing are called ultrasound (20,000 Hz and up). Duration is measured in seconds (s) and is the length of time that the subject is exposed to the sound. Sound levels in air and water are typically discussed as Sound Pressure Levels (SPL), with units of decibels (dB). The definition of an SPL is:

$$SPL = 10 \log (p / p_{ref})^2 = 20 \log (p / p_{ref}) \text{ dB re } p_{ref}$$

where

p = current sound pressure level in Pascals,

p_{ref} = reference sound pressure level in Pascals.

When referring to SPL values in decibels, it is critical that the reference pressure be included, because the reference pressure is dependent on the medium in which the sound in traveling. In air, SPLs are measured in decibels, referenced to 20 _Pa (20 x 10^{-6} pascals, or 20 micropascals). For water, a different reference is used: 1 _Pa. Often the notation will also include information about the distance from the source that the sound was measured, such as 165 dB re 20 _Pa at 1 meter.

Because studies performed in both air and water are discussed in this report, the appropriate reference pressure and measurement distance, when available, will be included. Converting between SPLs for air and water involves converting decibels back into Pascals and adjusting for the dramatically different acoustic impedances of air and water. A direct comparison of in-air and in-water levels is complicated by the significant differences in human hearing in air and water. A chart of relative sounds in air with their equivalent SPLs in water is shown in Table 5.1.

Table 5.1. Comparison of SPLs in Air[100,101]

Sound	Air Standard (dB re 20 uPa)	Water Standard (dB re 1 uPa)
Threshold of human hearing in air	0	62
Very quiet living room	40	102
Normal speech in air (1 meter)	60	122
Lion's roar, heavy trucks at 6 m	90	152
Jet airliner	104	166
Human threshold of pain	140	202
Military artillery	160-190	222-252

The decibel scale is based on logarithms, so dB values cannot be added together without reversing the logarithm scaling. Doubling the pressure only produces a 3 dB change, for example: 100 dB + 100 dB = 103 dB. 20 dB is 10 times the pressure at 0 dB; 40 dB is 100 times the pressure at 0 dB.

5.2.2 Which Bioeffect?

To have value as a deterrent, an acoustic non-lethal weapon must reliably produce a consistent Bioeffect in the human body. Acoustic energy, applied at specific frequencies, amplitudes, and durations from such a weapon, would affect the function and/or physical characteristics of major organs, limbs, or central nervous system in a measurable manner documented through animal and/or human testing. Without legitimate performance data, end users take a risk that the weapon will under perform (and have no effect) or over perform (and cause undesired serious injury or death).

With the exception of Navy studies on safe levels of exposure for divers to low frequency sound, [102-106] few reports have focused on specific extra-aural Bioeffects in swimmers or divers caused by exposure to sound. [107-109] The Naval Submarine Medical Research Laboratory, [106,110-119] Naval Experimental Diving Laboratory, [120-123] and others [124-127] have conducted relevant studies in diver hearing and diver physiology. A significant body of relevant research also exists regarding human Bioeffects caused by sound in air, particularly infrasound [128-155] and ultrasound, [156-162] relevant to this investigation.

The U.S. Army, the Air Force Biomedical Research Laboratory, and the Joint Non-lethal Weapons Directorate have also investigated the feasibility of high intensity, audio frequency sound as an "in-air" acoustic non-lethal weapon. [152,163-165] A recent Air Force Biomedical Research Laboratory report [166] examining animal Bioeffects produced by high intensity, audio frequency acoustic weapons in air, concluded that such weapons would be ineffective because the data failed to show useful, extra-aural Bioeffects from acoustic energy in audible frequencies up to 165 dB re 20 uPa (air).

The failure to identify a consistent Bioeffect for high intensity, audio frequency airborne sound does not imply that Bioeffects will not occur in water. The acoustic impedance of air is approximately 415 MKS rayls (kg/m^{2}s). In contrast, the average acoustic impedance of the human body is 1.6×10^6 MKS rayls, which is comparable to the acoustic impedance of water, approximately 1.5×10^6 MKS rayls. Thus, most airborne sound that reaches the human body is reflected due to the impedance mismatch, but waterborne sound passes directly from the water into the body. Table 6.2 [167 161] shows the relationship between the acoustic impedances of air, water, and components of the human body. Note that bone and lung impedances are the only significant deviations from the average of 1.6×10^6 MKS rayls. The moderate (6x) impedance mismatch between the lung and the rest of the body (and the surrounding seawater) provides the large reflection that allows divers to be located and tracked using an active swimmer detection sonar.

Table 5.2. Acoustic Impedances

Material	Acoustic Impedance (MKS rayls)
air (0° C)	428
air (20° C)	415
water (fresh, 20° C)	1.48×10^6
water (sea, 13° C)	1.54×10^6
blood	1.62×10^6
brain	$1.55\text{-}1.66 \times 10^6$
fat	1.35×10^6
kidney	1.62×10^6
liver	$1.64\text{-}1.68 \times 10^6$
muscle	$1.65\text{-}1.74 \times 10^6$
spleen	$1.64\text{-}1.67 \times 10^6$
lung	0.26×10^6
bone	$3.75\text{-}7.38 \times 10^6$

Most published studies related to underwater sound have focused on hearing capabilities and hearing damage among human subjects. Temporary threshold shifts (TTS) in hearing occur when humans are subjected to loud noises for brief periods of time, such as during rock concerts or when operating industrial machinery. [168] These shifts do not produce any reliably disabling Bioeffect. Exposure to higher levels and longer durations of noise in the audible frequency spectrum can result in permanent hearing damage that is acquired incrementally. Unfortunately, these types of studies are not useful to weapon development. Hearing is not a critical sense in the underwater environment and even total deafness has no effect on the ability of a diver to navigate into a secured area.

Most practical non-lethal weapons are effective because they cause the subject to experience physical pain and/or difficulty breathing. Similarly, any sound-based non-lethal weapon must somehow affect the diver's central nervous system causing pain, shortness of breath, vertigo, nausea, disorientation, or other systemic discomfort in order to be effective. Unless the sound produced by the weapon is audible, a well-trained diver may misinterpret some of these sensations as being related to problems with the inner and middle ear, arterial gas embolism or Type II decompression sickness. [42] This interpretation may affect the diver's reaction to those symptoms, as an experienced diver will follow procedures to deal with known causes of those maladies.

Breathing interference might be an effective Bioeffect because of the diver's dependence on supplied air. This Bioeffect would be likely to cause panic, resulting in the diver's uncontrolled ascent to the surface (and possible decompression sickness, depending on depth). [43,44] Interference with breathing is also the most likely Bioeffect to have significant, potentially lethal secondary results. [156,160,162,169]

5.2.3 Ultrasound

Application of acoustic energy at frequencies in the 1-4 MHz range, commonly known as ultrasound, has been widely utilized by the medical and dental community over the past 20 years for

imaging, heating and destruction of tissue, plaque removal from teeth, and acoustic microscopy. [161] In the industrial community, ultrasound is also used for cleaning, soldering, metal and plastic welding, electroplating, atomization, flow measurement, burglar alarms, pest control and other tasks. Many studies have evaluated the safe use and Bioeffects of ultrasound on adult humans. Ultrasound is also widely used to produce images of developing fetuses. Research on fetal Bioeffects of ultrasound is of particular interest because the fetus is suspended in amniotic fluid within the womb, much like a diver is suspended in seawater. [170-177] [171,178-190]

Heating and cavitation are the most common Bioeffects from exposure to ultrasound. The heating Bioeffect is useful during physical therapy, but tissue damage can occur if the exposure duration is too long. Figure 6.2 shows one estimate of the tissue temperature and duration thresholds for physical damage to organs caused by ultrasound.
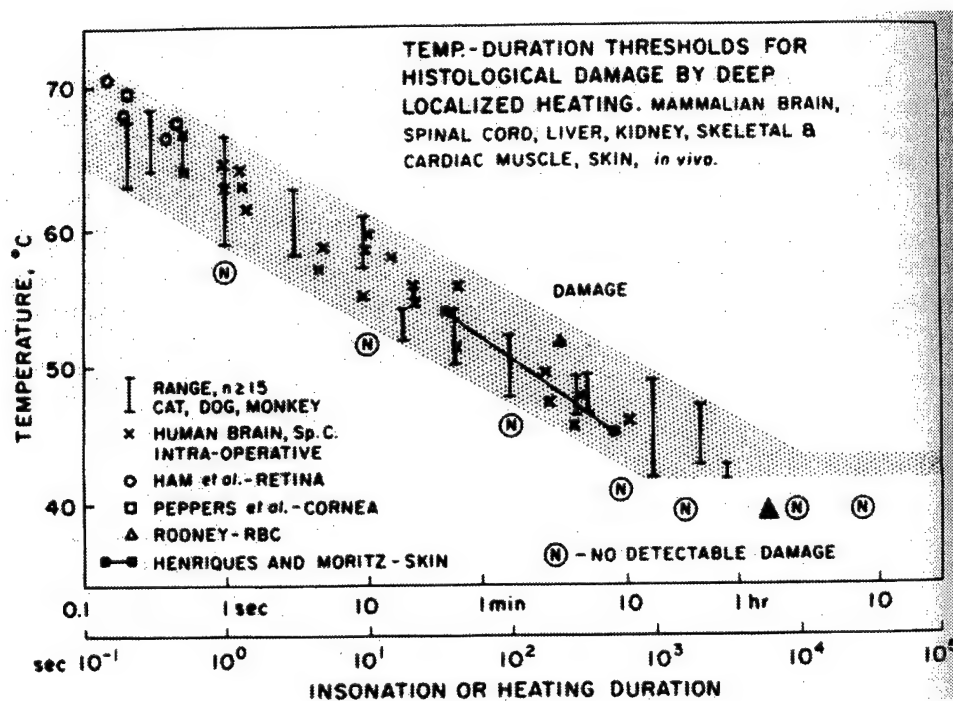
Figure 5.2. Thresholds for Damage Caused by Ultrasound [161]

In fluid mechanics research, the term cavitation indicates the formation of gas- or vapor-filled cavities in a liquid caused by mechanical or acoustic forces. During the rarefaction phase of the acoustic cycle, the local pressure becomes lower than the ambient pressure, and any bubbles preexisting in the liquid may begin to enlarge. During the next half of the cycle the local pressure rises, and the bubble size recedes. The degree of expansion, and the lifetime of the bubbles depend on several factors, including the acoustic pressure amplitude, ambient pressure value, wave frequency and duty cycle (if the sound source is pulsed), and the specific characteristics of the liquid and dissolved gases. Where the acoustic pressure is sufficiently high, bubbles will suddenly collapse releasing a large amount of energy almost instantaneously upon compression.

The specific question as to whether these Bioeffects could be produced in scuba divers exposed to underwater ultrasound was addressed by a U.S. Navy study. [115] The authors found insufficient experimental evidence to conclude that divers would face no biological hazard from exposure to

intense sound underwater at levels currently permitted. Thus, within those permitted levels, decompressing divers could be at risk. The report detailed the findings of a committee that included medical and acoustic experts in ultrasound and dive medicine. Current Navy policy, drafted as a result of this committee's findings and other research, is that divers operating near any sound source above 250 kHz may not be closer than 10 yards from the sound source to avoid experiencing any discomfort or injury-causing Bioeffects. [24]

For most applications, the ultrasound transmitter is placed very close to the object to be imaged. In air and water, the power of ultrasound rapidly falls off with distance. In general, energy at higher frequencies is absorbed more quickly by the surrounding air and water, while low frequencies will travel farther at higher energy levels. In the Navy study, the committee also evaluated whether the cavitation and heating effects could occur at lower frequencies. They observed that heating effects decreased rapidly with frequency, and at frequencies below 100 kHz, heating effects were negligible. Extremely high sound pressure levels are necessary for cavitation to occur in water. A diver would have to be within contact distance to the sound source to experience cavitation effects in the body. Since gas nuclei are always present in diver tissue, and existing decompression practice can allow bubbles to form in a decompressing diver, cavitation could cause increase in the amount of bubbles forming which would necessitate changes to the decompression process to guarantee the diver's safe ascent to the surface after exposure to ultrasound.

More recently, Crum and Mao [191] showed that for sound pressure levels (SPLs) in excess of 210 dB re 1 _Pa, significantly enhanced bubble growth can be expected and divers and marine mammals exposed to these conditions could be at risk. Another notable study examined damage in mice caused by exposure to ultrasound. [162] Adult mice were exposed to 20 second and 3 minute 2.3 MHz ultrasound at peak positive pressures ranging up to 3 MPa. Threshold pressures for the two exposures (before lung hemorrhage, 1.6 MPa and 1.4 MPa) were the same within the statistical significance of the measurements. Other studies also have found that lung and intestinal damage can occur in mice exposed to high intensity ultrasound at frequencies from 700 kHz to 3.6 MHz. [156,157,162] These studies indicate that for each type of injury the sound pressure level must exceed a certain intensity threshold for Bioeffects to occur in tissue, regardless of frequency.

5.2.4 Infrasound (1-20 Hz)

Various scientific claims have been made about the effects of infrasound on humans, beginning at least as early as the 1940s. [192] A large portion of the published literature focuses on two areas: continuous exposure (industrial and traffic noise), and sonic booms (aircraft). Many tests and studies were performed to assess whether long-term exposure to infrasound from road, airport, and factory noise would cause adverse health effects in those living near those facilities. [131,136-138,149-151,153,154,193-195] Some studies were general investigations into the effects of infrasound on humans. [133,196,197] Additionally, some data relating to research on the use of infrasound as a non-lethal weapon was reported in the U.S. [72-74] and U.K. in the 1970's. [94,96,132] Research into infrasound Bioeffects was also conducted in Russia during the 1980s and 1990s. [134,140,143-147,198-204]

Several sources report [94,97] that a "Sound Curdler" system purchased by the U.S. Army produced sound levels above 120 dB re 20 _Pa at 30 feet. One of the DISPERSE reports [72] references a proposal from Bowles Fluidics Corporation to build a device which may have been re-named the

"Sound Curdler." The device allegedly could produce disorientation and nausea, however no references or test data could be found to support these claims, or the claim that such a device was ever constructed. Similarly, another report [96] suggested that the British Army used a "Squawk Box" in Northern Ireland in the early 70's. This device allegedly used a ring modulator circuit to output the sum and difference of two frequencies (16,000 and 16,002 Hz), to produce 32,002 Hz (above audible range) and 2 Hz tones (infrasound). The British army officially denies using this device, and no supporting data could be located during this literature search. During this time period, other research data contradicted claims made by non-lethal weapons advocates. Harris et al.[150,151,205] investigated the effects of infrasound on humans. They found that sound levels had to exceed 100 dB re 20 _Pa (air) before effects were observed. Harris and colleagues argued that previous reports claiming Bioeffects resulting from exposure to 105-120 dB re 20 _Pa infrasound, were exaggerated since attempts by them and others [206] to reproduce the data found no effect on human reaction time or equilibrium, even at higher sound intensities. Another report by Bryan and Tempest [132] identified a voluntary tolerance limit for 60-100 Hz sound of 150-155 dB re 20 _Pa, but no evidence of permanent damage was observed for 5 minutes exposure to 160 dB re 20 _Pa at 196 Hz. However, some human subjects did complain of "painful resonances within the body" after exposure. This study cites a previous experiment in which exposure to tones in the 2-15 Hz band at 105 dB re 20 _Pa produced an increase in visual reaction time of 10% in half of the test subjects.

Perhaps Broner published the most complete review of existing research on infrasound. [207] The primary effect identified was annoyance, typically connected with long-term exposure to low-level infrasound. This Bioeffect would not be particularly useful for swimmer deterrence. Also, the threshold of pain for audible sound exposure is 140 dB re 20 _Pa (air) at 20 Hz, increasing to 162 dB at 2 Hz and 175-180 dB for static pressure. This threshold implies that very high levels of infrasound would be required to induce any Bioeffect. Evaluating studies on infrasound disrupting individual's equilibrium, Broner wrote that

> "Hood, Leventhall, and Kyriakides [208-210] found only two out of seven subjects affected at a level 110-120 dB, while Johnson [151] found no effect at levels up to 140 dB and Nixon [211] found an effect at 150 dB. The level (for any Bioeffect to possibly occur) is probably at least above 130 dB. It should be noted that these [recent, 1970s] studies (showing no Bioeffect), were all of short duration (8 minutes maximum) exposure while in those by Hood, Leventhall, and Kyriakides, etc…showing performance decrement, exposures of 30 minutes or more were used."

Broner's overview also noted that infrasound had been used to promote relaxation, stimulate brain waves (7 Hz is the median frequency of the alpha rhythm [198]), and enhance the audio portion of motion pictures (the "Sensurround" system used for *Earthquake*, *Roller Coaster*, *Midway*, and other movies of the 1970s). [212] One study used blasts of high intensity sound to attempt to produce ovulation in women with glandular deficiencies, and electrical stimulation of the brain at 42.5 Hz was claimed to rectify color blindness. Not all measured Bioeffects of infrasound are undesirable. Russian researchers investigated the use of infrasound to treat myopia in school children, and some changes in the vascular membrane were observed. [144] Much of the data summarized in Broner's review are contradictory and inconclusive. The author concludes that many of the claims regarding the effects of infrasound are "overrated," although he states that high-level low frequency noise in the range of 20-100 Hz causes more significant effects than infrasound at the same intensity level.

Interest in infrasound was renewed in the 1990s, and data from new studies was reported. Landstrom determined that hearing perception was directly related to the Bioeffects of infrasound. [138] Sound levels must exceed the hearing threshold in order to have any Bioeffect. This work was supported by studies that evaluated effects of occupational exposure to infrasonic noise in Poland. [141,213] Hearing thresholds for infrasound were 65 dB re 20 _Pa at 32 Hz, 95 dB re 20 _Pa at 16 Hz, 100 dB re 20 _Pa at 3 Hz, 140 dB re 20 _Pa at 1 Hz for the subjects studied. For those same subjects, the threshold for aural pain was 160 dB re 20 _Pa at 3 Hz. Luszczynska found that a close correlation existed between the exposure to infrasound, its perception, and its physiological effects, such that the sound pressure levels had to be high enough to be physically perceived in order to produce physiological effects in the subjects. Luszczynska also referenced several additional studies, including one report in which deaf subjects were shown to be "immune" to the effects of infrasound because they could not hear it. Recent work into the use of infrasound as an acoustic barrier for fish farms indicated that unlike humans, fish and eels are acutely sensitive to infrasound, [214,215] which implies that use of infrasound for swimmer deterrence could potentially change normal behavior of indigenous aquatic life.

Reportedly, new data on the effects of infrasound was recently generated in Russia. References to this work appear in a translated paper on sonar technology, [198] and as well as in a recent book summarizing possible non-lethal weapon technologies. [46] The Mit'ko paper [198] reviewed Russian papers concerning Bioeffects of infrasound. [216-224] However, efforts to obtain copies of these Russian papers for inclusion in this report were unsuccessful.

The Mit'ko review cites claims that exposure for extended time brought on impairment in tracking ability, choice-reaction time, and peripheral vision in human studies and identified 7 Hz as a specific frequency that caused difficulty in mental activities and precision work. While these reports have been cited by SARA in support of their development of non-lethal acoustic weapons, [99,225] SARA's translations of these papers were in verbal, summary form only, [226] and full English translations of the complete articles do not exist in written form at this time. From a scientific perspective, it is difficult to accept any claims made in the untranslated papers as to the Bioeffect of infrasound without further review.

During the literature search for this review, no studies were found in which the effects of infrasound on divers were tested. Given the lack of clear evidence pointing to useful Bioeffect, there is no justification to recommend that infrasound be considered for swimmer deterrence. As Bruner observed, the frequency band between 20-100 Hz, to be discussed later in this report, may be of greater significance.

5.2.5 Audible Sound

Audible sound is typically defined as frequencies in the range from 20-20,000 Hz. Because their frequencies are outside human hearing range, extra-aural Bioeffect from exposure to infrasound (1-20 Hz) and ultrasound (above 1 MHz) involve organs and systems other than the ear. Bioeffects caused by audible sound may include aural and extra-aural components. Any aural components are dependent on diver hearing response, and the human reaction to verbal commands, irritating sounds, or sounds at a pain-inducing volume level.

5.2.5.1 Diver Hearing

Since divers frequently operate in a low visibility environment, command presence and hand signals are difficult to project to the diver. Verbal commands or other auditory signals, however, can be used to alert an intruding diver that they have been detected by security personnel and that failure to surface or leave the area may result in non-lethal or lethal force being used. The critical issue in this form of swimmer deterrence is the ability of the diver to hear the signal and understand speech, if verbal commands are used.

The early work in measuring underwater hearing began in 1967 with Brandt and Hollien, [227] and during subsequent years the Navy has continued to measure and evaluate diver hearing capabilities and hearing damage that may result from exposure to explosions, underwater tools, sonar and other hazards. [110,117,118,121,228,229] In water, human hearing occurs primarily as a result of bone conduction, which occurs when sound is transmitted into the middle and inner ear through the skull, rather than the eardrum. [228] A summary of diver hearing investigations [230-233] indicated that the threshold of hearing ranges from 20-75 dB at 1 kHz and 20-40 dB at 125 Hz, [234] with maximum underwater hearing sensitivity located around 500-1000 Hz. These reports claimed the ear underwater is more sensitive to low frequencies (below 1 kHz) due to diminished amplification from head diffraction and the external ear resonance underwater, and a 27 dB reduction in sound transmission through the middle ear when the diver is submerged.

In air, the "A" weighted scale in Figure 5.3 is used to adjust sound pressure levels to the human hearing response, which is best between 500-5000 Hz and poor for frequencies below 500 Hz. The "UW" weighting scale, as proposed by Parvin and Nedwell, [235] can be used to compare human hearing response in air and water. In water, peak hearing capability is at 800 Hz, with the human ear most sensitive to frequencies from 400-1000 Hz. The loss in sensitivity between 1000-5000 Hz may make it difficult for divers to understand speech underwater, if broadcast from an underwater loudspeaker. Speech intelligibility depends on our accurately perceiving speech in approximately the 1500-3000 Hz ranges much more than in the frequency ranges above or below this band. [101] A significant increase in amplitude of the frequencies in the 1000-5000 Hz band could compensate for the sharp drop in diver hearing sensitivity for frequencies above 1000 Hz and increase the likelihood that a diver would understand specific words. In addition to showing the change in hearing frequency response in air and water, the figure above also shows the substantial decrease in overall sensitivity. In water, human hearing is 30-40 dB less sensitive on average, which raises the threshold of pain.
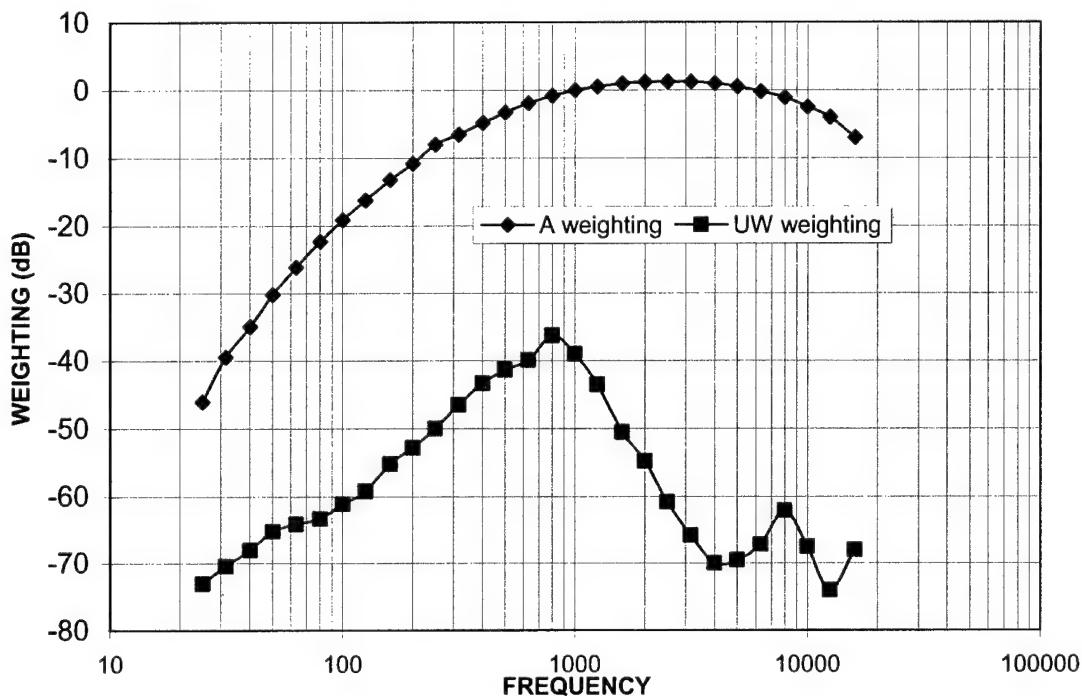
Figure 5.3. A and UW weighting scales [236]

A number of studies have been performed to determine discomfort thresholds for audible underwater sound. In 1961, Montague and Strickland [237] tested the sensitivity of the water-immersed ear to high and low level tones. They found that the tolerance limit for divers without wetsuit hoods was 174 dB re 20 _Pa (air standard). Wearing a wetsuit hood, divers were able to tolerate levels in excess of 180 dB. These tests were performed using tones at 1500 Hz, of 1 second duration, 2 seconds apart. When subjected to continuous tones above 165 dB, divers reported distortion of the visual field, likely caused by over stimulation of the vestibular (inner ear and equilibrium) system. Kryter [238] reports that in air, similar vestibular system stimulation occurs at SPLs on the order of 130-140 dB re 20 _Pa.

A literature review conducted in 1989 [239] noted that two different methods were used to evaluate underwater-versus-in-air hearing capabilities and thresholds, with one method yielding a difference of 25-30 dB and the other having an average difference of 37 dB. The latter value is close to the acoustic impedance difference between air and water, which may be significant. It is also the number that one might expect for improved bone conduction hearing caused by better coupling when immersed in the water medium. Immersion in water is not the only factor producing a change in diver hearing. In 1969, Paul Smith [117] measured a 25-35 dB reduction in hearing sensitivity at 1000 Hz in divers wearing wetsuit hoods. A later experiment at Naval Submarine Medical Research Laboratory (NSMRL) measured 10-15 dB reductions in hearing sensitivity in divers wearing wetsuit hoods. A literature review conducted in 1989, [239] concluded "sufficient evidence exists that for depths up to at least 30 feet divers' hoods offer a significant amount of acoustic protection at frequencies of 1000 Hz and above, and little or no protection of 250 Hz and below."

Another hearing-related capability that is reduced in water is sound localization. In normal humans, the brain interprets the differences in the signals between the left and right ear (loudness,

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time delay, and other cues) to determine whether the sound source is to the left or right. [240]
Underwater, this capability is diminished. [241] According to Paul Smith, of the U.S. NSMRL [114]

> "The impedance of soft tissue is not much greater, sound is readily
> transmitted from water to the cochlea through those tissues, bypassing the
> acoustically inefficient tympanic route. That is, the ear canal is acoustically
> transparent in water, and man's ossicular chain is not effective in water
> primarily because the ossicles lack sufficient mass. Further, because of cross-
> conduction through the skull, the two cochleae are not independently
> stimulated under water as they are in air, and hence sound localization is not
> possible for man in water."

However, later studies [126,242] [118] found that intensity cues may not be as robust as "time of arrival" information with respect to underwater sound localization. In these studies, divers were able to localize the direction that an impulse noise (explosive diver recall device) was deployed from. Noise signals, rather than pure tones, were easier for the divers to localize. At frequencies below 400 Hz, humans may rely more on phase information, rather than intensity differences, to localize sound. [243]

The study of diver hearing is relevant to swimmer deterrence because sound is the only method by which commands to exit a protected area can be given to a swimmer or diver. As previously discussed, commercial acoustic diver recall devices, such as those produced by Oceanears [244] (shown in Figure 6.4), Lubell, [245] Nautronix, [246] and others provide a capability for surface boat personnel to speak to all divers within the effective range of the device. The cost of acoustic diver recall devices ranges from $1,000-6,000. Testing should be performed to compare the maximum range and intelligibility vs. cost for commercially available systems. It may be possible to improve range and intelligibility of these devices by equalizing the signal transmitted into the water to compensate for the frequency response of diver hearing. That experiment should be part of any evaluation of acoustic diver recall systems, as the equipment required to adjust frequency content could be as simple as a commercial audio equalizer costing $200 or less. Adding the capability for one-way communication from patrol boat to diver is the least expensive, lowest risk, and most legally defensible action that should be taken to improve current capability for swimmer deterrence.
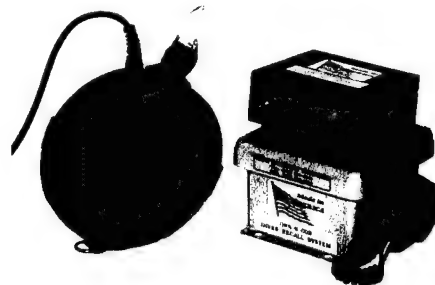

Figure 5.4. Oceanears Acoustic Diver Recall System [244]

5.2.5.2 Fetal Studies

Acoustic research data from experiments performed on human and animal fetuses were reviewed for this report. Results from those studies may be relevant to human response to underwater sound, because a fetus is suspended in liquid, similar to a diver. The majority of the studies addressed

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hearing and the effects of loud noise on the fetus. [173,247-258] Niemtzow [259] measured the attenuation resulting from tissue and fluid surrounding the human fetus to be 20-25 dB for 50-200 Hz, 25-30 dB for 500 Hz, 40 dB for 1000 Hz, 50 dB for 2000 Hz, and 70 dB or more for 4000 Hz and higher frequencies. Another study reported similar results, with attenuation in the womb increasing with frequency. These data correlated well with diver hearing response data, which peaks at 800 Hz and drops off sharply at frequencies above 2000 Hz. Two fetal sheep studies also supported this result. A study of temporary threshold shifts demonstrated that low frequencies were transmitted into fetal sheep, but higher frequencies were significantly attenuated. [177] A second study, found that sound pressures generated by low frequencies (<250 Hz) were 2 to 5 dB greater inside the womb than outside the pregnant ewe. Above 250 Hz, sound inside the womb decreased at 6 dB per octave. [260]

Another area of fetal research relevant to this study is the Bioeffect of vibroacoustic stimulation. Electronic recording of fetal heart rate patterns following vibroacoustic stimulation has been used for many years to evaluate fetal well being. Accelerations provoked by vibroacoustic stimulation are generally accepted as a normal response in healthy fetuses. [180] The test is performed by placing an artificial larynx to the maternal abdomen over the area of the fetal head. Depressing the button causes a loud vibrating sound (100-120 dB re 20 _Pa at 1000 Hz) and produces a significant vibratory stimulus. The background noise level in utero is reported as 60-80 dB re 20 _Pa. Typically the stimulus lasts from one to ten seconds. [109] Exposure to this unexpected noise causes an increase in fetal heart rate, which is monitored before, during and after exposure to the sound source. In a few rare cases, exposure to this test has resulted in serious negative consequences for the fetus, such as neonatal arterial flutter [185] and fetal bradycardia. [184] In general, however, exposure to this unexpected sound produces only transient changes in heart rate related to the startle response. [180,181]

5.2.5.3 HEARING-RELATED BIOEFFECTS

The DISPERSE [72] researchers, as part of their 1975 study, also recommended the evaluation of irritating or pain-inducing sounds, such as the sound of fingernails being scraped down a chalkboard, or very loud sirens, as non-lethal weapons. [74] The scientific study of our perception of sound and tone, and which characteristics make certain tones pleasing and others irritating, dates back to the late 1800s. [261] As sound recording and reproduction technology has advanced, many devices, from the Aphex "Aural Exciter" to the Dolby™ surround sound processor, have been invented to "sweeten" music and speech by selectively adjusting frequency and phase in stereo and multi-channel systems. The field of psychoacoustics studies human perception of sound, and most modern sound processors exploits specific Bioeffects that most people with normal hearing perceive as pleasurable.

Reversing these effects to create sounds that are specifically unpleasurable has been a popular suggestion of many non-lethal weapon advocates for decades. Perhaps the most famous use of sound as an irritant was during the Branch Davidian siege in Waco, Texas. [262,263] FBI hostage negotiators played recordings of Tibetan prayer chants, screaming and dying rabbits, and other sound "irritants" as part of the effort to get the Branch Davidians to surrender. This tactic was unsuccessful, and as Harvard University psychiatry and law professor Stone [264] noted in his report to the Justice Department:

> The constant stress overload is intended to lead to sleep-deprivation and
> psychological disorientation. In predisposed individuals the combination of

physiological disruption and psychological stress can also lead to mood disturbances, transient hallucinations and paranoid ideation. If the constant noise exceeds 105 decibels, it can produce nerve deafness in children as well as in adults. Presumably, the tactical intent was to cause disruption and emotional chaos within the compound. The FBI hoped to break Koresh's hold over his followers. However, it may have solidified this unconventional group's unity in their common misery, a phenomenon familiar to victimology and group psychology.

The failure of the FBI's use of sound as an "irritant" in this situation tragically illustrates that psychoacoustics is based on assumptions about human psychology, which are rarely valid for all people. Those who might decide to illegally enter a protected area with criminal intent would likely not fit the psychological profile of "normal," and may not respond as a "typical" person would. However, irritating sounds have been used to drive away less committed loiterers. For example, use of pink lighting and playing Bing Crosby records over the PA system are keeping idle youth from congregating in front of stores in Mareela, Australia. [265] A determined mindset can enable a committed attacker to overcome a purely psychological deterrent, making irritating audible sound a poor choice.

The U.S. Army has recently investigated the use of painfully loud audible sound as a non-lethal weapon. Several sound sources were evaluated, and animal testing was performed to assess target effects. Human subjects were provided with hearing protection to prevent hearing damage, [266] but in the animal testing, deafness resulted from exposure to these high intensity sounds. [165] It is well known that exposure to loud noises can cause temporary and permanent hearing threshold shifts, [101] depending on exposure time. If the primary Bioeffect of the weapon is discomfort caused by high volume, it can be expected that the weapon will cease to work if the victim quickly becomes permanently deaf from exposure to high intensity sound. The researchers concluded from these studies that pain generated through the auditory system due to high intensity sound was not a useful Bioeffect due to the high risk of permanent hearing damage.

5.2.5.4 ACOUSTIC DETERRENT DEVICES USED BY FISH FARMS

Irritating audible sounds are currently used in the commercial fish farm industry to repel marine mammals from fish farms. The performance and environmental impact of these Acoustic Deterrent Devices (ADDs) remains a controversial issue. [267] The idea of using acoustic signals to repel marine mammals from fish farms was first developed in the 1970's. The first generation of ADDs was developed to deter pinnipeds from fishery areas and hatcheries and was first used on fish farms in British Columbia in 1988. [268] The early units produced signals between 12-17 kHz at an output of about 180 dB re 1 µPa at 1m. This signal was intended to be unfamiliar and unpleasant because it was in the range of maximum hearing sensitivity of harbor seals and California sea lions. The general success of these devices was short-lived and in most cases animals habituated and returned to feed in close proximity to the sound source within a few seasons. [269,270,271,272]

In the early 1990s, new, more powerful ADDs were developed that produce signals in the range of maximum hearing sensitivity of seals and are of such power that animals do not easily habituate. At close range they potentially could cause pain or injury. Two models were used along the British Columbia coast: the Airmar "dB Plus" developed by Airmar Technology Corporation and other models by Ferranti-Thompson Sonar Systems. The Airmar device produces a signal of 194 dB re 1 µPa at 1m with the energy narrowly concentrated at 10 kHz with a strong harmonic at 20 kHz. The

Ferranti-Thompson 'seal scrammer' produces a signal at 38.4 kHz at a level of 205 dB re 1 μPa at 1m. [273] Ferranti-Thompson has developed a triggering system for their unit so that the motion created by a seal hitting the net activates the unit. This triggering system has been reported to be unreliable in practice. [268]

As of 1996, about 20% of the fish farm sites in British Columbia used the new ADDs. Reeves et al.[274] Report that the new ADDs were effective for up to two years. Seals that have successfully attacked are much harder to deter than naïve animals. [271,274,275] Seals that experienced success exposed themselves to the intense sound and may have suffered hearing damage. No hearing tests were performed on seals known to have been exposed to the ADDs. [269] The potential harmful effects of the new high-power ADDs on other marine mammal species were also studied. Because marine mammals, cetaceans in particular, rely extensively on sound to communicate, navigate, hunt and avoid predators, there was a very real concern that the sounds produced by ADDs could interfere with these basic survival needs. The hearing of toothed whales is many times more sensitive to sounds in the 10-20 kHz band than that of harbor seals (approximately 20 dB more sensitive). [276] In a 1994 study along the Broughton Archipelago, [277] harbor porpoise sightings declined precipitously when the ADD was activated. The response to the ADD by harbor porpoise extended over a distance of least 3.5 km, the maximum range of the study area. These results were highly significant and could not be attributed to any other variables. Pulsed Power Technologies Incorporated (PPTI) [278] developed an ultrasonic Sea Lion Deterrent Device under a grant from the National Marine Fisheries Service. The device used compressed ultrasonic waves (above 1 MHz, far above the hearing range of marine mammals) to allegedly drive sea mammals away from boats, leaving fish undisturbed. [279] Additional information about this device appeared in an August 2000 report from the Sport fishing Association of California, which reported that in December 1999 the California Coastal Commission had unanimously denied the request for a permit to test the PPTI unit. [280]

Richardson et al.[276] Describe four zones around an acoustic source in assessing the effects of man-made noise on marine mammals: the zone of audibility (the largest zone), where the animal might hear the noise; the zone of responsiveness, where the animal would react behaviorally or physiologically to the sound; the zone of masking, where the noise level is high enough to interfere with detection of other sounds, such as communication signals, echolocation signals, prey sounds or other natural marine sounds; and the zone of discomfort or hearing loss. Based on known or inferred auditory capabilities, 10 kHz ADD signals would be audible to other cetacean species found in British Columbia coastal waters [281] such as harbor porpoises, Pacific white-sided dolphins, Dall's porpoise, killer whales, humpback whales, minke whales and gray whales. Data reported in a summary paper by Iwama et al.[268] Indicate that the behavior of many species are adversely affected by noise in the 10-20 kHz band, and the authors recommended that the use of ADDs at fish farms be phased out of all fish culture operations within two years.

Based on the data reviewed for this study, use of ADDs developed for fish farms for swimmer deterrence is not recommended, due to documented environmental impact on marine mammals and the absence of data for any human Bioeffects resulting from exposure to 10-20 kHz sound.

5.2.5.5 Extra-Aural Bioeffects

In high intensity audible sound experiments involving human subjects, extra-aural (unrelated to hearing) Bioeffects have been observed. As previously noted, anecdotal data regarding the effects of

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sound on various internal organs and the central nervous system has existed for decades. Typically, these Bioeffects have been related to exposure to frequencies below 1000 Hz, and related to resonance frequencies of internal organs, or central nervous system effects.

5.2.5.5.1 Low Frequency (100-500 Hz)

During the 1990s, the Navy conducted studies on the effects of low frequency sound (100-500 Hz) on divers to determine safe levels of exposure as well as the results of unsafe exposure. The Bioeffects investigated included auditory shifts, vibrotactile sensitivity change, muscle contraction, cardiovascular function change, central nervous system effects, vestibular (inner ear) effects, and chest wall/lung tissue effects. Organizations involved with this research program included the Naval Submarine Medical Research Laboratory (Groton, Connecticut), Navy Experimental Diving Unit (Panama City, Florida), SCC San Diego, Navy Medical Research and Development Command (Bethesda, Maryland), Underwater Sound Reference Detachment of Naval Undersea Warfare Center (Orlando, Florida), Applied Research Laboratories: University of Texas at Austin, Applied Physics Laboratory: University of Washington, Institute for Sensory Research: Syracuse University, Georgia Institute of Technology, Emory University, Boston University, University of Vermont, Applied Physics Laboratory, Johns Hopkins University, Jet Propulsion Laboratory, University of Rochester, University of Minnesota, University of Illinois, Loyola University, and the State University of New York at Buffalo.

The first report from this research program, released in 1996, [102] primarily consisted of a literature review, with some new work in analytic modeling of the chest/lung interface and cavitations, hypothermia and tissue shearing. [282] The interaction of rectified bubble diffusion with decompression stress was the subject of new theoretical development. [283] The researchers found that cavitations, hypothermia, and tissue shearing could be significant for low frequency sonar exposure, and no follow on experiments were recommended. Tests on human divers were performed, [169] and no lung resonance effects were observed due to exposure to the 160-320 Hz bands, which was the primary frequency range of interest in these studies. Recommendations for exposure of Navy divers to sound in the 160-320 Hz band were proposed, based upon data from these U.S. and U.K. reports. The proposed recommendations included a maximum SPL of 160 dB re 1 _Pa, with continuous exposure of no more than 100 seconds, at a maximum duty cycle of 50%, with a maximum exposure time of 15 minutes per dive day, and nine days of exposure in a 14 day period.

Cudahy et al summarized a second set of experiments in 1999.[116] This work focused on the evaluation of Bioeffects of sound in the 100-500 Hz range. Research included testing on small animals and humans. Mice, rats, and guinea pigs were used to evaluate the risk of tissue damage resulting from low frequency sound exposure at the resonant frequency of major organ systems. These studies included control groups of animals that were submerged (while breathing on a ventilator) but not exposed to underwater sound. Damage risk thresholds were always measured at lung resonance frequency and above, so that any effects observed did not result from damage to the lungs. This data was then reflected as a generalized debilitation of the animal rather than injury to the specific organ system under investigation.

Using an acoustic scattering technique to measure the lung resonance frequency in mice and rats, Dalecki [105] found that the lung resonance frequency {in Hz (f_0)} varied as a function of body mass {in grams (w)} according to the following relationship:

$$f_0 = 742 \, w^{-0.25}$$

These data indicated that the resonance frequency of the lung varies with body mass. According to Dalecki's formula, the lung resonance frequency for a 150 lb person occurs at approximately 45 Hz. Predictions based on this compare favorably with the observed lung resonance frequencies of divers collected during the human testing phase of these experiments.

Results of low frequency sound exposures at lung resonance indicate that there is no observable lung damage in guinea pigs at SPLs up to 170 dB re 1 μPa (water). Between 170 and 175 dB, however, the level of lung damage increases with increasing sound pressure level (SPL). Similar tests performed on mice by Dalecki [105] show that the threshold for both lung and liver damage occurs at about 184 dB and increases rapidly as intensity is increased. The mouse lung resonant frequency averaged 328 Hz, ± 25 Hz. Vestibular effects were observed in guinea pigs using 160 dB SPL signals at the lung resonance frequency and 190 dB SPL signals at 500 Hz. [284] However, results on these measures of vestibular performance were highly variable between animals with 50% of the animals showing no decrement in horizontal vestibular ocular reflex. No decrement was found in any animals exposed at a lower level of 150 dB SPL. As with other results from this phase, these data indicate that Bioeffects only occur once the SPL has exceeded a threshold level. Other animal tests from this phase showed that cognitive function in rats was not impaired by exposure to low frequency sound; however the exposures were of lower level (150 dB SPL) and were not at the rats' lung resonant frequency.

Human tests were performed with divers suspended at a 1-meter depth, and exposed to low frequency sound in the 100-500 Hz band. [102,103] These tests measured hearing thresholds for low frequency sound, indicating that SCUBA exhaust bubbles can mask low frequency sounds. As the frequency of the sound decreased from 400 to 100 Hz, hearing thresholds increased (higher levels are required at lower frequencies for the diver to notice the sound). At SPLs above the hearing threshold, divers began to detect vibration in various body parts. The air filled cavities of the lungs, abdomen and head were the most common locations of observed vibration. Nearly all subjects detected vibration when exposed to 100 Hz, 130 dB re 1 μPa (water) sound, but as frequency increased, and the probability of detecting vibration decreased.

In the same diver tests, higher levels of exposure were used to determine aversion response. At an SPL of 140 dB, none of the subjects exceeded an aversion rating of "Very Severe" for the frequency range 100-500 Hz. At the highest SPL tested (157 dB), divers reported an aversion level over "Very Severe" 19% of the time. The frequencies divers found most objectionable were 100 Hz and 250 Hz, with 100 Hz the most objectionable. [106,116] Immediately prior to and immediately following one of the dive studies, the subjects performed an extensive battery of tests designed to assess if the LFS exposures affected neuropsychological and vestibular functioning. Analysis of pre- and post-dive scores revealed no adverse cognitive or hearing effects resulting from exposure to low frequency sound. Additional measurements made on heart rate and vascular effects indicated that no significant Bioeffects on those systems occurred from these exposures to low frequency sound. A theoretical analysis of the shear forces that could result from focusing and de-focusing effects of the long wavelength associated with low frequency sound suggested that increasing amounts of soft tissue damage may occur at SPLs beyond 186 dB re 1 μPa. [285]

Cudahy and colleagues [116] included a tabular summary of Bioeffects of low frequency sound (100-500 Hz), based on their research findings (Table 5.3).

Table 5.3. Summary of Bioeffects for 100-500 Hz Sound [116]

Sound Pressure Level (dB re 1 uPa)	Bioeffect
80-100	Divers first detect the presence of sound through auditory mechanisms
< 130	Divers begin to detect low levels of vibration in various body parts
136–140	The majority of divers tolerate the sound well with only "slight" aversion
140–148	A small number of divers rate their aversion as "very severe," especially for 100 and 500 Hz frequencies
148–157	The loudness and vibration levels become increasingly aversive. Some divers may contemplate aborting an open water dive
157	No significant decrements or damage in physiological, neurological or cognitive systems have been observed following exposures to LFS at or below this level for continuous sound for up to 28 seconds, and cumulative sound exposures of 14 minutes. However, it is estimated that at least 20% of divers will immediately abort an open ocean dive if exposed to this sound level.
160	5 minutes of continuous exposure at lung resonance may induce significant decrements in vestibular function
170–184	Lung hemorrhaging observed in rodents during exposures at the lung resonant frequency. As the resonant frequency of the human lung is considerably lower than 100 Hz, it is likely that much higher SPLs are required to induce significant damage to the human lung for exposures in the 100-500 Hz range.
> 184	Liver hemorrhage and soft tissue damage are likely.
> 194	Based on animal data significant concussion effects are unlikely to occur below this level

Based on these findings, Navy Diving Manual guidelines were revised as follows:

"Because the probability of physiological damage increases markedly as sound pressures increase beyond 200 dB at any frequency, exposure of divers above 200 dB is prohibited unless full wet suits and hoods are worn. Fully protected divers must not be exposed to SPLs in excess of 215 dB at any frequency for any reason." [24]

In the Navy diving manual, specific guidance is given for exposure to a variety of submarine and shipboard sonar, including: AN/SQS –23, -26, -53, -56, AN/BSY-1, -2, and AN/BQQ-5, for wet suit un-hooded, wet suit hooded, and helmeted divers. Minimum diver distance from the sonar is calculated from a maximum exposure time of 13 minutes in a 24 hour period, and these distances range from 13 yards to over 2,000 yards, depending on the specific sonar in question and diver equipment. These sonar typically have high source level and transmit at frequencies of 2 kHz and higher. Guidelines are also given for higher frequency systems such as the AN/SQQ-14, -30 and –32 sonar, which are also shipboard sonar. Exposure times and distances for these systems are based on a maximum exposure time of 120 minutes, at ranges from 2 to 13 yards. All of these sonars also have

high cost, and very large transducer arrays, which make them unsuitable for patrol boat or pier side use.

However, if available, transmissions from the low frequency sonar described above could have a deterrent effect on scuba divers. It should be noted, however, that the literature search conducted for this report did not locate any studies specifically showing that these sonar produce known Bioeffects in divers when the ranges and time limits listed in the Navy Diving Manual are exceeded. Because the guidelines were developed from the same body of research results presented in this report, it is reasonable to assume that they are the best estimates that can be drawn from existing data, and that divers will experience varying degrees of injury as a result of exceeding the manual's guidelines.

Two specific cases in which exposure to sound produced noise-induced neurologic disturbances in divers were discussed in which divers developed immediate, and long term problems associated with exposure to continuous low frequency tones for durations longer than 15 minutes. [286] The report states that

> "Potential mechanisms of underwater sound-induced neurologic dysfunction, derived from experimental work on the effects of airborne sound and vibration, include central nervous system (CNS) stimulation mediated through a cochlear pathway, direct CNS stimulation from water-borne sound or vibration, and underwater sound-induced vestibular stimulation. A CNS effect initiated from primary cochlear stimulation is the most likely mechanism to account for most non-auditory effects observed from in air exposure, and would logically apply to underwater noise exposures as well.
>
> Of perhaps greater concern is the possibility that the underwater sound affected brain tissue through direct physical stimulation. The state described by the subjects, and the observations of on site medical personnel, resemble the symptoms of individuals who have suffered minor head injuries. Thus, one theory for a causal mechanism would be that the prolonged sound exposure resulted in enough mechanical strain to brain tissue to induce an encephalopathy.
>
> Finally, these subjects' symptoms may also be viewed as being consistent with sound-induced stimulation to the otolith organs, which detect linear motion. The production of vestibular signs or symptoms by an acoustic stimulus is commonly referred to as the 'Tullio phenomenon'. [287,288] It has been suggested that intense sound exposure may damage the vestibular receptors with or without concomitant damage to the auditory portion of the membranous labyrinth. Thus, vestibular symptoms may occur without concurrent effects on hearing."

5.2.5.5.2 Extra-Aural Bioeffects in Humans

Other studies have evaluated the effects of high intensity sound in the audible frequency range on divers. In 1986, Martinik & Opltova [289] published experimental results indicating that exposure to infrasound, broadband white noise and pure low frequency tones (125-500 Hz) can cause measurable changes in heart rate and blood pressure, but those Bioeffects are very inconsistent from individual to individual. This hypothesis is supported other research by Broner [207] and Harris. [150] Studies have also been performed assessing the effects of specific drugs on reactions to sound exposure.

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[81,82,290-296] These studies are worth noting here as supporting research on general Bioeffects, but are of little specific relevance because none of the observed Bioeffects are immediate and incapacitating. It is unrealistic to assume that intruding divers would have taken the particular drugs (and dosages) studied in these experiments.

Based on a review of existing literature in 1981, Pearson recommended an upper limit of 180 dB re 20 µPa for all frequencies [297] as the maximum amplitude that divers could be exposed to for short periods of time. He also stated that frequencies below 500 Hz cause Bioeffects at lower (unspecified) sound pressure levels. An NSMRL study [112] found that wet suited and hooded divers could work for useful periods of time while subjected to tone pulses at sound pressure levels up to 191 dB. Non-auditory effects that accompanied exposure to very high sound levels in water were found to be annoying but not immediately harmful to divers. Divers were subjected to 3500 Hz tone pulses 25% and 50% duty cycles for durations up to one hour. Non-auditory effects included spraying of water within facemasks, perceptible pressure, and visual field displacements. When divers were within visual range of the transducer, exposed to sound levels 212-218 dB, direct acoustical stimulation of the vestibular apparatus (Tullio effect) occurred. As a result the divers experienced dizziness and other disorientation.

In 1992, the Sea Search Company contacted the Naval Investigative Service Command with information regarding its "Anti Diver Deterrent Integrator," which claimed to deter divers through high sound pressure levels. The letter referenced in this report [298] claimed that the system had "undergone extensive field tests in the U.S. and U.K." The company also claimed to have produced extra-aural effects in a diver 15 meters from an AN/SQS-53 equivalent transducer, when 480 Watts of power at 4.6 kHz was input to the transducer. The single anecdotal data point presented in the company's letter did not include the sound pressure level nor duration of sound exposure, which makes this claim difficult to assess. The literature search performed by the authors was unable to locate any test reports from U.S. or U.K. tests of this system, but an observer who attended a demonstration of this system at Naval Air Station Paxtuent River, Maryland [243] reported that divers involved in the demonstration described the system as "unpleasantly loud" when 50-100 yards away.

NSMRL studies performed by Smith et al.[111] Found that 10- and 15-minute continuous exposures to 125-6000 Hz tones caused temporary threshold shifts but no other Bioeffects. However, other studies observed Bioeffects at high noise levels,[299] and predicted that divers exposed to high noise levels could experience hearing loss, vertigo, nausea and vomiting. [230] As part of the Navy's recent evaluation of the effects of low frequency sound on divers, [119] divers were exposed to 196 dB tones between 500-4000 Hz. Many reported joint pain, dizziness, alterations in visual fields, and headaches. During this study a diver was exposed to more than 15 minutes of continuous 250 Hz warble tones (±12.5 Hz), and experienced significant medical problems as a result. That incident was reported in detail in the paper on noise-induced neurologic disturbances [286] discussed earlier in this report.

Recent data from the U.K. [300] reports that bareheaded divers terminated exposure to 880-2200 Hz tones at levels from 176-185 dB re 1 µPa due to vestibular effects (dizziness) and overall loudness, but divers wearing wetsuit hoods did not terminate exposure to levels at 191 dB. Those same test divers rated the sound as "loud, but not disturbing" at an average level of 150 dB when bareheaded, and a level of 165 dB when hooded. Pre- and post-dive evaluation of diver hearing, balance, ECG/heart rate, and lung function showed no significant post-dive effects.

5.2.5.5.3 Very Low Frequency (20-100 Hz)

The recent studies on Bioeffects from exposure to high intensity 100-500 Hz sound were primarily motivated by a desire to set safe exposure levels for divers for specific low frequency sonar. In several of those studies, Bioeffects related to lung resonance were observed in animals with lung resonance within the 100-500 Hz regions. Because the human lung resonance is in the 20-100 Hz band, typically 30-50 Hz, these Bioeffects were not considered significant to the 100-500 Hz study. However, that data indicated diver exposure to high intensity sound in the very low audible frequency band may result in stimulation of internal organs, including the lungs, or effects on the vestibular system. The authors of the 1999 NSMRL summary report wrote:

> "Although no empirical data is available on the minimum SPL required to induce lung damage at lung resonance frequency, present models of the human lung predict that the greatest amount of tissue strain with LFS will occur in the central airways at frequencies between 30 and 40 Hz. If tissue damage in the lung were caused by excessive tissue deformation then these model predictions would indicate that the greatest chance for damage to the lung tissue would occur for low frequency sound exposures at frequencies close to the observed lung resonance frequency.

> Despite occasional extreme ratings for aversion, loudness and vibration, none of the sound exposures (to sound within the 100-500 Hz band) resulted in an uncontrolled or unsafe ascent to the surface. Many subjects were noticeably nervous immediately prior to conducting the underwater sound exposures. This nervousness was confirmed by their state anxiety scores, heart rate and respiratory rate, which were significantly higher, pre-dive than post-dive. During a post-test debriefing, 21% of the subjects indicated that they would abort a dive if they were exposed to these sounds (up to 157 dB SPL) during an open water dive." [116]

Wave transmission in the lungs was studied using an acoustic model. [284,301] The model predicted that within the frequency range of 0-300 Hz, significant pressure amplification can occur within the airways and at increased depth a gas density increase causes a decrease in the frequency at which resonance occurs. This finding was counter to the prediction by Minneart [302] that lung resonance would increase as depth increases, but experimental data supports Minneart's analysis.

Lung resonance was studied in experiments in the U.S. (Georgia Tech) [169] and the U.K. [235] The Georgia Tech experiments measured the lung motion of five divers in response to incident acoustic signals in the frequency range of 50-140 Hz, first at the surface of a pool and then at 10-foot depth. All five divers showed a lung motion peak in the vicinity of 100 Hz during the surface measurements, but this peak was absent when the measurement was repeated at a 10-foot depth. The reason for the disappearance of the 100 Hz peak was not identified from analysis of the data from this experiment. The U.K. researchers exposed four divers to broadband noise in the frequency range of 15-1500 Hz at a sound pressure level of 160 dB re 1 μPa (water standard). The divers were instrumented to measure incident waterborne sound level, intrabuccal sound pressure, sternal acceleration, and mask acceleration. The data indicated that lung resonance frequency increased with depth.

In another experiment conducted at Georgia Tech in 1999 [104] human lung resonance was determined by multiple techniques at the surface and at pressures equivalent to 10 feet of seawater

(FSW), 60 FSW and 120 FSW. Results indicated that the human lung resonance frequency is approximately 40 Hz at the surface and increases as a function of depth to 80 Hz at 120 FSW. These data confirm previous tests and measurements made of this parameter and support Minneart's hypothesis that lung resonance increases with depth.

Percy and Duykers [303] investigated the effects of sound on large mammals. Measurements of lung resonance were made for dolphin, domestic swine and human divers. During the tests at frequencies below 100 Hz, one diver (head above water) reported sensations of vibration in the chest at an SPL of 135 dB re 1 μPa (measured 2m from the diver). The lung resonance frequency for this diver was found to occur at 70 Hz. Subsequent tests on seven Navy divers at depths of 6 m using a variety of breathing apparatus and wearing wet suit or not for all cases the resonance frequency was found to be between 30-40 Hz. Initial work with domestic swine [304] investigated high intensity exposures for 3-7 kHz and 40-80 Hz. Previously the total lung resonance of domestic swine had been reported to be between the 40-80 Hz. The 3-7 kHz exposures at SPLs 191-214 dB re 1 μPa for 30-90 seconds appeared to produce slight but consistent alveolar damage. The low frequency tests (also at lower SPLs) produced no damage. A study of underwater hearing in the clawed frog [305] also reported response peaks related to resonance of the lungs and air-filled middle ear cavity. A study of the effects of low frequency sound on the hearing of oscar fish (*Astronotus ocellatus*) [229] reported that the only damage observed was for exposure to 300 Hz tones at 180 dB re 1 μPa. No damage was observed for exposure of fish to 60 Hz tones.

Additional data on the effects of low frequency sound on divers was reported by Mit'ko. [198] The author identified the 40-60 Hz band as related to lung resonance and notes that tests were performed in the 5-100 Hz band with a 110 dB re 20 μPa level (in air), which translates to a minimum level of 136 dB re 1 μPa in water to produce any effect. As previously noted in this report, Navy researchers working on the 100-500 Hz investigations hypothesized that it was possible to induce lung discomfort and lung damage through exposure to high intensity sound near the lung resonance frequency. [116] Recent data reported by Parvin [300] confirmed that divers exposed to low frequency noise (15-200 Hz) observed Bioeffects at 130 dB and terminated exposure due to lung, body and head vibration at 172 dB.

A review of low frequency sound (1-1000 Hz) and its effect on marine mammals performed by the National Research Council in 1994, [100] found almost no quantitative information with which to assess the impact of low frequency noise on marine mammals. For those few marine mammals on which hearing sensitivity data was available, low frequency sound, even at very high levels, is barely audible. The report did not address any extra-aural effects on marine mammals that might occur as a result of exposure to low frequency sound. Other research cited in this report indicated that an acoustic swimmer deterrent device capable of stimulating lung resonance or other Bioeffects in humans might produce similar results in some marine mammals. Recent data published by SSC-SD indicates that single pure tones of one second or less at Navy sonar frequencies (between 400 Hz and 75 kHz) are not likely to produce a shift in hearing until the mammal's received SPL reaches or exceeds 192 dB re 1 μPa. [306 307 308,309]

Another Bioeffect, which may be produced by very low frequency sound, is the Tullio effect, or direct acoustic stimulation of the vestibular system. As Parker noted in 1978,

> "During the period from 1930 to the present time, several investigators have reported responses indicative of vestibular stimulation following exposure of human beings to high intensity acoustical stimulation. Nystagmus

(involuntary oscillation of the eyeball elicited by vestibular or optical stimulation) has been observed following exposure to pure tones ranging from 200 to 2500 Hz at intensities from 120 to 160 SPL re 20 μPa (air). Dizziness, nausea, and disturbances of postural equilibrium have been correlated with sound stimulation at intensities and frequencies lower than those, which are required to evoke nystagmus. These responses are believed to reflect activation of vestibular receptors; however, the possibility that dizziness, nausea, and equilibrium disturbance result from acoustical stimulation of physiological systems in addition to the one associated with vestibular receptors has not been completely eliminated." [310]

In a 1993 review of the vestibular role in sympathetic regulation, Previc [311] reported that vestibular stimulation could elevate or depress heart rate, blood pressure and ocular reflex as well as cause or prevent motion sickness. He hypothesized that vestibular interaction with the sympathetic and parasympathetic systems was complex and not consistent with a single type of autonomic influence. This statement is supported in part by anecdotal data scattered throughout the Navy studies. Generally, the Tullio effect has been observed in patients with abnormal development of the vestibular system, or in victims of head trauma. [287,288,312] Researchers in Finland [312] measured the effect of exposure to 30 seconds of very low frequency sound (25, 50 and 63 Hz tones) at 130-132 dB (air). Subjects were divided into two groups: normal and those with vertigo. Normal subjects were unaffected by the low frequency sound exposure; in subjects with different types of inner ear disease the vestibular system responded to exposure to low frequency sound. In 1982 Hartman studied 365 university students who frequented discos and were exposed to music at levels above 120 dB (air). [313] Of that group, 82 exhibited Tullio symptoms, and 44 had both audiometric loss and Tullio symptoms, indicating that continued exposure to high intensity; low frequency sound could cause the Tullio effect. Dizziness was reported by all test divers in the recent U.K. study on sound exposure. [300]

Unfortunately, data on Bioeffects in the 20-100 Hz band is scarce, as most experiments have focused on infrasound, or higher frequency audible sound. From the results of all the experiments and studies reviewed for this report, it is likely that the 20-100 Hz band is the one most likely to cause lung and/or vestibular discomfort. The most consistent factor in noise induced Bioeffects is not frequency, but intensity, with exposure time of nearly equal importance. However, for the specific problem of Bioeffects in divers, the lower frequencies may yield results at lower intensities due to the impedance match between tissue and seawater, and the impedance mismatch between lung tissue and surrounding tissue.

A number of systems, both existing and proposed, are capable of producing high intensity sound in the 20-100 Hz band. Historically, this frequency range has been the most difficult to produce using traditional piezoelectric transducers. Other approaches such as air guns, spark sources, and explosives are more commonly used. Spark sources and explosives produce impulse noise, which is high intensity, short duration sound with the majority of its energy below 500 Hz. Impulse noise will be discussed in a following section. Two proposals to build systems for producing narrowband, or single frequency sound in the 20-100 Hz band were located during the literature search. One system, proposed by Lockheed Martin, [314] was intended to produce high intensity sound at 32 Hz. The proposal claimed that the device would have Bioeffects of "intolerable discomfort, including visual distortions, mask and sinus vibrations and thorax vibrations" for 175 dB SPL. At 6 m, a diver would allegedly be exposed to 200 dB and risk permanent physical damage. Another proposal, from

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Weidlinger Associates, [315] describes a design for an air-gun based sound source capable of producing 4-10 Hz high intensity sound, claiming that low frequency resonance of the visceral organs in the thorax and abdomen will be excited, producing discomfort. The Lockheed proposal contained no references or data supporting their Bioeffect claims; the Weidlinger proposal used a single reference to the Shock and Vibration handbook. Many of the summary papers studied in the preparation of this report warn against using a single study, or single anecdotal data point to infer the existence of a "universal" Bioeffect. Despite the lack of evidence for claims made in these commercial proposals, the body of literature reviewed for this report indicates that exposure to high intensity sound in the 20-100 Hz band may cause discomfort in swimmers and divers. The data also indicates that no single frequency will be effective on all intruders, which implies that any potential non-lethal swimmer deterrent device should be capable of producing broadband sound in this very low frequency band.

5.2.5.6 Impulse Noise (Startle Response)

The majority of the studies discussed thus far have all focused on continuous or pulsed tones and their effects on humans and animals. Another type of sound is impulse noise, typically produced by explosives, firearms, and other black- or gunpowder based weapons. Explosive distraction devices are commonly used by law enforcement SWAT teams as distraction devices, [31] and explosive "diver recall devices" are also used in diving activities. These devices can produce a startle response, which is a Bioeffect that may have value in swimmer deterrence.

The startle response in reaction to unexpected impulse noise in air has been studied by researchers interested in the effects of aircraft sonic booms, [170,316-319] reaction to gunfire, [320-325] and other noise-related Bioeffects. [326] A 1975 report on sonic booms [327] showed that the intensity of the startle effect increased with the amplitude of the impulse noise: at 65 dBA the subject was annoyed; at 71-74 dBA autonomic eye-blinks and arm-hand movements occurred in some subjects; at 81-84 dBA 90% of the subjects blinked and arm-hand movements occurred in 57%; and at 92-96 dBA 96% of the subjects made reflex arm-hand movements. Repeated exposure to the booms (at equal intensity) decreased subsequent reactions. [328] Von Gierke & Nixon [211] found that the effect of sonic booms from aircraft caused a muscular startle response. Momentary decrements in performance were observed for the more intense booms, measured immediately after the stimulus. In 1976, Kryter investigated extra-aural Bioeffects due to noise and concluded that people were not likely to be at risk from the possible autonomic stress responses to noise. [329]

In a more recent study, [330] British researchers showed that the eye blink is an auditory reflex, not part of the subsequent true startle response. The normal startle reflex results in eye closure, grimacing, neck flexion, trunk flexion, slight abduction of the arms, flexion of the elbows and pronation of the forearms. In some subjects only eye closure and flexion of the neck was apparent. The blink reflex persisted despite the repetition of the auditory stimulus every minute. Other researchers concluded that startle reflex magnitude was increased when the activating signal was unpleasant or related to unpleasant memories. [331] This study reported that fear-conditioned stimuli (such the fear of being killed or captured) increase the startle reflex. This result was supported by a study of the startle reaction in Vietnam veterans suffering from posttraumatic stress disorder (PTSD) [332] (Orr, Lasko, Metzger, Pitman) that concluded that people with PTSD have bigger reactions to startle tones and more normal reactions to non-startling sounds.

An investigation of the role of auditory stimuli in sudden cardiac death found that 10% of sudden death victims had no identifiable heart defects. Some of those cases, in retrospect, occurred after exposure to sudden loud noises. The researchers hypothesized that neural stimulation from auditory pathways stimulated cardiac sympathetic nerves, and that the startle reflex increased sympathetic activity predisposing the heart to ventricular fibrillations. Some patients were also diagnosed with long QT syndrome (an infrequent, hereditary disorder of the heart's electrical rhythm that can occur in otherwise-healthy people). Topaz and colleagues [333] concluded that startling loud noises may occasionally cause otherwise unexplained cardiac arrest in some individuals. A similar study by Moss [334] found that cardiac arrest resulting from exposure to loud noise could occur under special cases of genetic and clinical conditions.

A test of a prototype in-air impulse noise acoustic non-lethal weapon was conducted by Air Force researchers. [166] In one experiment, [152] the effect of high intensity acoustic impulses on the behavior of monkeys was tested. The Sequential Arc Discharge Acoustic Generator (SADAG) sound source was capable of pulsing at frequencies up to 20 Hz. The primary goal of the test was to evaluate the effects of infrasound, not the startle response due to audible impulse noise. The SADAG has an output over 165 dBA (in air, A-weighted), with a majority of the energy at frequencies above 2000 Hz. The monkeys were given hearing protection for the test, and no behavioral changes were observed when the primates were exposed to the sound source.

In a second test, pigs were used as test subjects, and no hearing protection was provided. When the sound source was turned on, the pigs moved as far away from the sound source as possible, and showed no interest in returning to the bar press food station. The pigs were still physically capable of movement, but they found the sound source so aversive that they chose to remain hungry. When the experiment was repeated, the pigs became agitated when placed in the test chamber, and refused to go anywhere near the bar press food station. One problem with this experiment is that the sound source also produced a bright flash and an "ozone smell" along with each sound pulse. Although an optical barrier was used to block the flash, researchers noted that it is possible that the pigs' aversive reaction to the SADAG may have been related to a combination of sound, sight and smell and not the sound pulse alone. [335]

Clearly, the trend in these experimental results is that loud impulse sounds induce an autonomic reflex, and the intensity of that reflex is influenced by the subject's psychological state and the presence of other sensory cues. While the startle reflex alone will not cause incapacitation, it could contribute to diver panic. In *Anxiety and Panic in Recreational Scuba Divers*, Morgan [43] claims that panic is under-reported and under-rated as a cause of diver fatality in the recreational diving community. He reported that many stressors could cause diver panic including: vertigo, hyperventilation, blurred vision, sensation of suffocation, or fear of immediate death/injury in response to an unanticipated event. Similarly, National Marine Fisheries Service officials, commenting on the potential environmental impact of a planned Navy test involving underwater explosions, state that the potential for a startle response to have serious consequences for humans is high, because the diver is in an unnatural, hazardous and unpredictable environment. [306 307 336] It may be possible or desirable to induce one or more of these stressors in a diver to deter him from remaining in a secured area. It may be possible or desirable to induce one or more of these stressors in a diver to deter him from remaining in a secured area.

One approach to producing high intensity impulse noise is controlled explosions. Studies of explosive diver recall devices by the Navy Experimental Diving Unit (NEDU) [122] evaluated the

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U.S. Army M-80 detonation simulator, which was also in use at the time by the Navy diving community. The study found that the M-80 was poorly suited for diver recall because it was classified as a class A explosive making storage and transportation extremely difficult. The M-80 required excessive modification to function as a recall device, and the acoustic output varied dramatically from device to device. Other commercial devices were tested and the Broco MK 2 MOD 0 was judged to be the best, based on a combination of safety and effectiveness tests. At the time of the study (1991), the Broco MK 2 MOD 0 devices cost approximately $16 each in prototype form, with production cost estimated at $12 each. The NEDU study evaluated safe sound pressure and blast pressure levels, and determined that the Broco device was safe if used more than 10 m from the diver. The Broco device was still audible at a range of 500 m.

Earlier NEDU tests of audible recall devices [121] [123] defined 175 dB re 1 μPa as the recommended limit for diver exposure to impulse noise, with an absolute upper limit of 186 dB. The safe exposure limit for blast pressure was defined as 2 psi-msec (2 pounds per square inch pressure exposure in a 1 millisecond period). The impulse noise was described as very loud, but not uncomfortable. The frequency of one device's impulse was measured at 200-300 Hz, and no damage to lungs or gastrointestinal tract was observed. The report notes that damage would have been expected had the impulse energy been in the 50 Hz regions.

Exposure to high intensity impulse noise can produce temporary and permanent threshold shifts in hearing depending on the noise intensity. At higher intensity levels, physical effects related to blast overpressure can also occur. An Army study [337] exposed cats to howitzer and rifle blasts and measured hearing shifts related to impulse noise with different frequency distributions. Howitzer noise contained fewer high frequency components than rifle fire. The NEDU [120] evaluated threshold shifts caused by impulse noise from an underwater tool with an 185 dB re 1 μPa peak. Temporary threshold shifts were observed, but no other effects noted. Other researchers [338] have performed animal studies to assess bladder, lung, and liver damage at threshold over pressure. Related studies of marine mammal sensitivity to single underwater impulses conducted at SSC-SD indicate that a temporary threshold shift in mammal hearing is not likely to occur until the received SPL reaches or exceeds 226 dB re 1 μPa. [306] [307] [308,309] Explosives have remained the weapon of choice against scuba divers for many decades: used by U.S. forces during the Vietnam conflict, [339] and in use by foreign navies today. [340] Typically explosives are targeted directly at the diver, but as described in this section, low-shrapnel explosive devices could be used for signaling as well as intimidation of approaching divers as non-lethal force. Sufficient data exists on safe limits for sound pressure and blast exposure to determine whether specific explosive diver recall devices pose a health hazard to divers. It should be noted, however, that the startle response due to impulse noise is primarily an annoyance, and the use of explosive recall devices does not cause any significant physical impairment of the diver's abilities to maneuver or continue an attack.

5.2.5.6.1 Plasma Sound Source

As observed in previous sections, there is no magic frequency, no Star Trek phaser weapon that is a definitively safe but effective non-lethal weapon to deter swimmers and scuba divers. In the review of existing and emerging technologies, one technology was noteworthy because it has the potential to provide psychological and (possibly) a physiological deterrent to swimmers and divers. The technology is a spark gap sound source, similar to that previously tested in air at Brooks Air Force Base. [166]

Spark gap sound sources, also known as Plasma Sound Sources (PSS), have been built at ARL: UT for use as very low frequency sonar transmitters. [341,342] The technology is relatively simple: charge is stored in a large, high voltage capacitor bank, and when the PSS is fired, all the stored energy is released in an arc across electrodes in the water. The underwater spark discharge creates a high-pressure plasma/vapor bubble in water. The expansion and collapse of this bubble generates an acoustic signature similar to the signatures generated by air guns, [354] underwater explosions, and combustible sources. [343]

Underwater spark discharges have been used as active sources in such roles as sub-bottom profiling and bistatic sonar. [344] Spark sources produce impulse noise with the majority of the energy within the 20-200 Hz band, have a high source level (215 dB re 1 μPa), and can rapidly pulse. The frequency characteristics of the output pulse can be tuned by adjusting the mechanical design of the electrodes. [345] ARL: UT has already built and demonstrated a boat-deployable, portable configuration, and used that system in open water in the Gulf of Mexico. [344] Firing of the PSS caused no obvious environmental impact, but specific effects on divers have not been tested. One company producing a commercial plasma sound source reports that continuous operation of the PSS for more than 3 months can kill zebra mussels attached to underwater pipelines. [355].
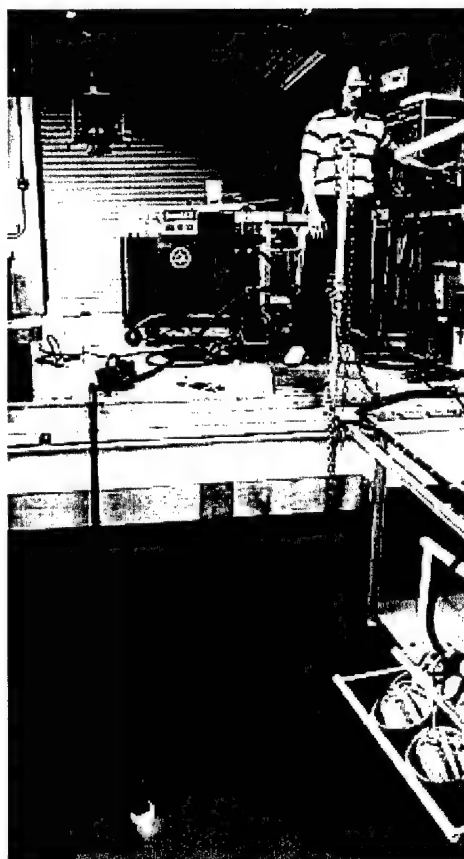

Figure 5.5. Plasma Sound Source electrode in water [341]

In 1992, a report from the Office of Technology Assessment (OTA) on harbor security described a device advertised by GT Devices (a subsidiary of General Dynamics) called the Underwater Deterrent Security System. This device was promoted as a non-lethal human swimmer defense system, which was an array of PSS electrodes. One prototype system consisting of a 16-element array was built for test purposes. GT Devices claimed that the 16-element device had a focus spot only a few meters wide at a range of 200 meters. The OTA states that for a number of reasons, neither the Defense Nuclear Agency nor the Navy chose to fund advanced development of the GT Devices system. [346]

The PSS is an attractive candidate for swimmer deterrence because it can be pulsed randomly or repetitively, which would allow it to be used for infrasound or startle response Bioeffects. The majority of its sound energy occurs in the 20-200 Hz regions, where data indicate that the most likely lung and vestibular effects will occur. In addition to producing sound, it also produces a bright flash, which was visible, in air, when the electrodes were 300 feet underwater. [344] The PSS produces no shrapnel or projectiles, is electronically activated, has an adjustable, calibrated power level, and can be deployed from a pier or a medium- to large patrol boat. Limited anecdotal data, collected during PSS testing at ARL: UT's Lake Travis facility, indicates that divers find it "very unpleasant." ARL: UT dive team members refuse to be in the water, even on the surface, when the PSS is operating. [347] Based on the results of this investigation, it is recommended that the PSS be evaluated, through animal and eventual human testing, as a swimmer deterrent device.

Figure 5.6. Plasma Sound Source Fired in Small Swimming Pool [341]

6. ELECTROMAGNETIC DEVICES

Other directed energy non-lethal weapons are beginning to emerge, such as the Active Denial System [348] developed for the Marine Corps. This microwave weapon causes a burning sensation, like touching a hot light bulb. The device operates at 95 GHz with a 100 kW source. [349] Unfortunately, seawater absorbs high frequency energy much better than air, which means that the microwave weapon would be ineffective. The microwave weapon transmits a narrow beam of energy, which would be difficult to target against a subsurface threat at unknown depth.
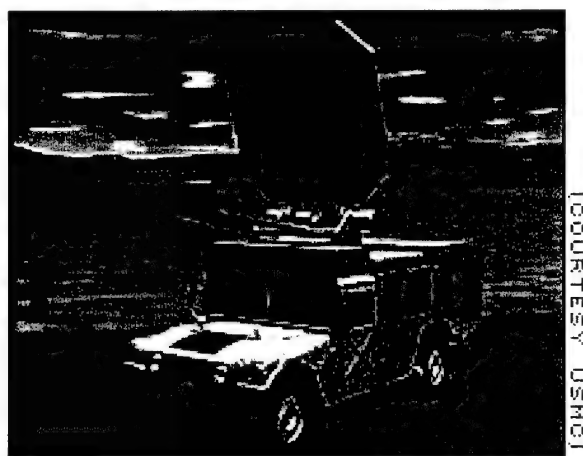

Figure 6.1. Active Denial System [348]

The effects of electromagnetic fields on humans have been studied [194,350,351] primarily in relation to long term exposure to electrical power lines, and at present no significant Bioeffects have been identified in normal humans. One study reported that exposing test subjects suffering from muscular dystrophy to weak magnetic fields improved reticular sensory-motor integration. [350]

The use of magnetic fields to attack diver equipment was considered, since tanks and compasses might be affected by a strong magnetic field. One approach was to drag a loop of wire beneath a patrol boat, and put sufficient current through that loop to generate a magnetic field, which would cause a diver's compass to read incorrectly, thus causing the diver to veer off course. A rough calculation [352] showed that it would take approximately 7 kW of power to energize a loop of wire that would significantly affect the earth's magnetic field down to a depth of 15 feet below a patrol boat. As the wire loop size increases, unfortunately, the power requirement increases exponentially. To affect the magnetic field down to 30 feet, for example, would require 64 times more power, or 448 kW. In order for this approach to be effective, the loop would have to be deployed from a patrol boat near the diver, which implies that a large power source supplying high current would have to be installed on a patrol boat.

7. TOWARD A NON-LETHAL SWIMMER DETERRENT DEVICE

Future research into swimmer deterrence should involve additional animal and human testing similar to that performed in the recent U.S. Navy and Joint Non Lethal Weapons Directorate studies on low frequency sound Bioeffects in air and water. Specifically the Bioeffects of exposure to high intensity sound in the 20-100 Hz band, and high intensity impulse noise, should be studied to determine if lung function or vestibular activity is affected, and whether those Bioeffects are both discomforting and temporary. No non-lethal swimmer deterrent weapon should be fielded without this essential performance verification step.

8. SUMMARY

All existing and emerging technologies appropriate for use as a swimmer deterrent were evaluated through literature review and discussions with users and researchers. In general, the most promising solutions are acoustic in nature, because of the high cost and/or performance potential or availability of other technologies. The law enforcement use-of-force model was applied to the waterfront security swimmer problem, and the following recommendations were made:

(1) Waterfront "command presence" should be improved by the presence of appropriately equipped patrol boats and floating barriers that clearly mark the boundaries of protected areas.

(2) The capability to clearly communicate verbal commands to a diver should be improved. Commercial acoustic communication systems [244,245] [353] designed for diver recall should be standard equipment on waterfront security patrol boats. In the fall of 2001, U.S. Navy Waterside Security System and U.K. diver hearing researchers will conduct a comparison test of commercial acoustic diver recall devices. This testing will include intelligibility [354] and maximum range measurements and an evaluation of whether those attributes can be improved by modifications, which will compensate for the frequency response of diver hearing. [236] The results of that test will be reported in a separate document.

(3) Acoustic sound sources producing high intensity, very low frequency sounds are the only technology capable of providing large area coverage at a reasonable cost. Additional testing is necessary to determine which specific frequencies and power levels are required to cause temporary discomfort of sufficient intensity to motivate approaching swimmers or divers to abandon their intrusion into a protected area. It is also recommended that any sound source used as a swimmer deterrent be used only in response to a high threat condition or swimmer detection sonar alarm, to minimize any environmental impact caused by the high intensity sound. As with other non-lethal weapons already in use, any future acoustic non-lethal weapon will have varying degrees of effectiveness, and may fail to deter, or may permanently injure or kill a certain percentage of those exposed to its output. As explained previously these risks are inherent to all weapons, both lethal and non-lethal. Given the existing need for a non-lethal response and the Navy's lack of existing capabilities in this area, continued investigation of sound sources identified in this report, particularly those which emit sound in the 20-100 Hz band, is strongly encouraged.

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14. ABSTRACT

The Applied Research Laboratories, The University of Texas at Austin (ARL: UT) was tasked to study the means and equipment for non-lethal methods to deter swimmers and scuba divers from restricted areas. This work included identification and evaluation of existing technologies, as well as review of research in security, acoustics, biology, and other fields. Various technologies have been developed as non-lethal weapons for law enforcement, but most of them are not suitable for deterring swimmers and scuba divers, because they are not designed for subsurface use. These existing technologies, as well as equipment currently used for diver deterrence and communication, were evaluated in this study.

15. SUBJECT TERMS

Mission Area: Ocean Surveillance
swimmer deterrent   waterfront security
sparkgap sound sources

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